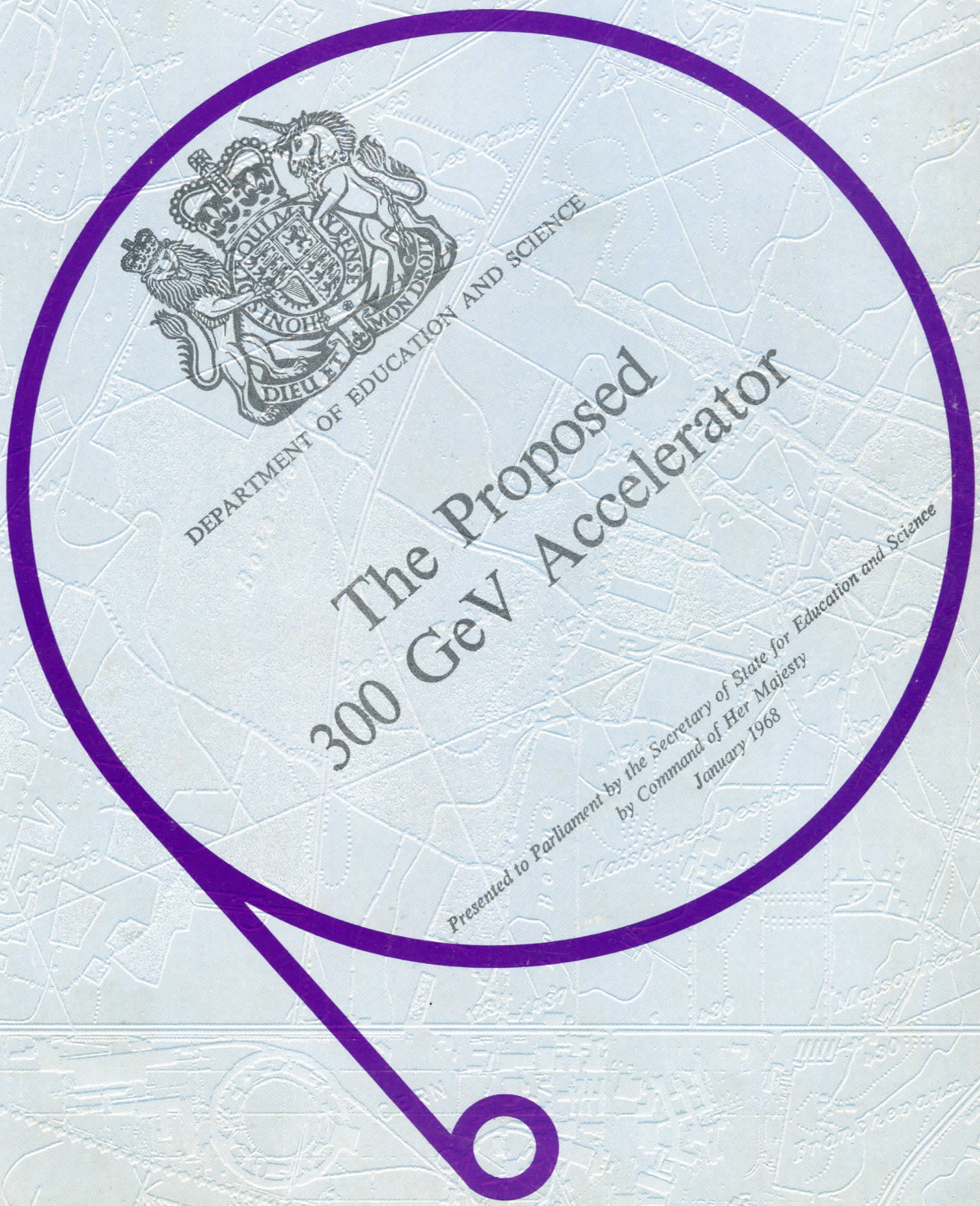
S100 33 and 34

THE OPEN UNIVERSITY

Science Foundation Course Units 33 and 34

Science and Society


DEPARTMENT OF EDUCATION AND SCIENCE
The Proposed
300 GeV Accelerator
Presented to Parliament by the Secretary of State for Education and Science
by Command of Her Majesty
January 1968

The Open University

Science Foundation Course Units 33–34

SCIENCE AND SOCIETY

Prepared by the Science Foundation Course Team

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This text is one of a series that, together, constitutes *a component part* of the Science Foundation Course. The other components are a series of television and radio programmes, home experiments and a summer school.

The course has been produced by a team, which accepts responsibility for the course as a whole and for each of its components.

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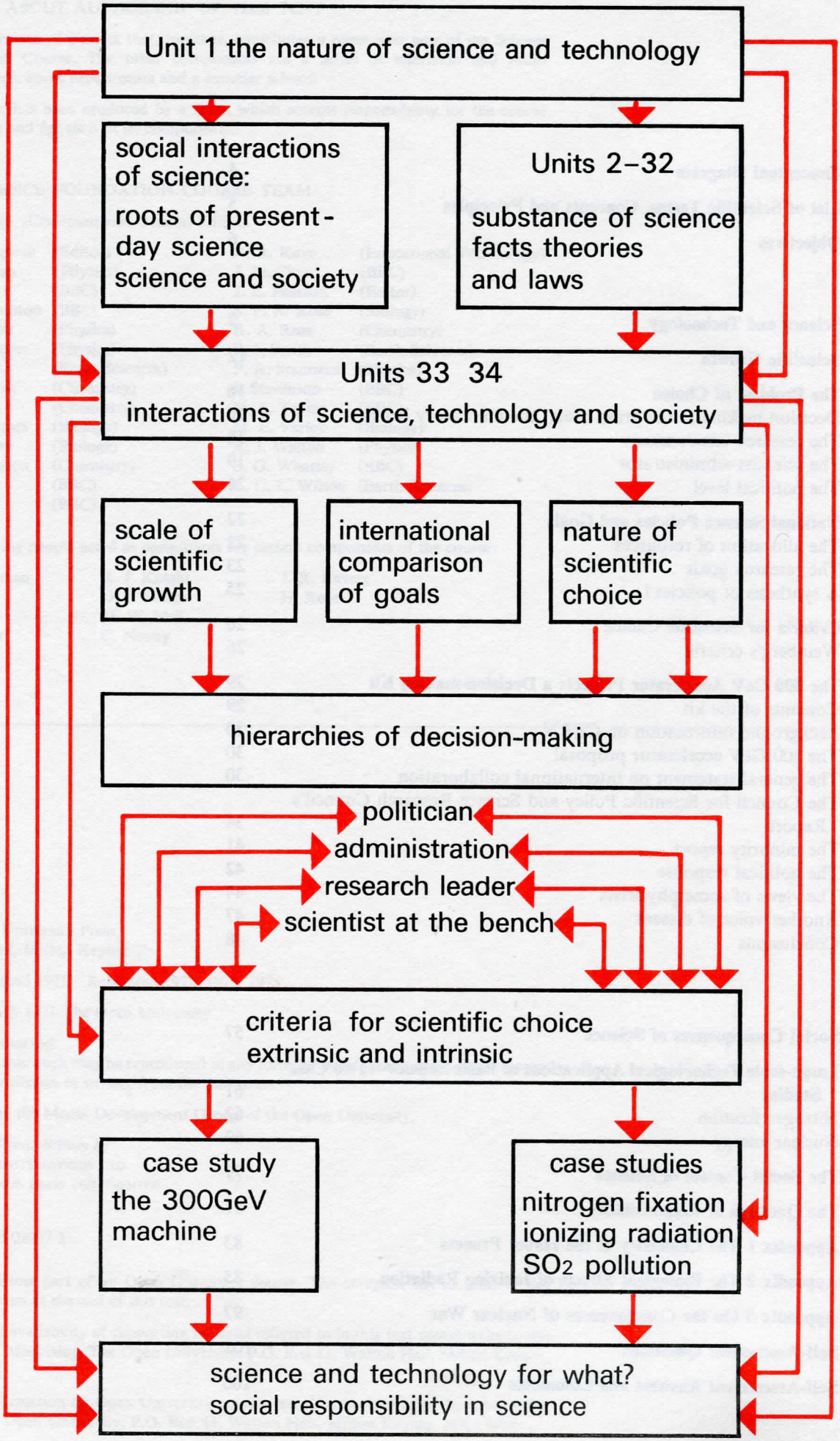
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case study
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case studies
nitrogen fixation
ionizing radiation
SO2 pollution
science and technology for what?
social responsibility in science

Table A

List of Scientific Terms, Concepts and Principles used in Units 33 and 34

Taken as pre-requisites			Introduced in this Unit			
1	2		3		4	
Assumed from general knowledge	**Introduced in a previous Unit**	**Unit No.**	**Developed in these Units**	**Page No.**	**Developed in a later Unit**	**Unit No.**
gross national product (GNP)	science	1	exponential growth	12		
	technology	1	scientific growth	12		
	fact	1	'big science'	14		
	law	1	'little science'	14		
	internal logic	*Science*	levels of scientific decision-making	16		
	external logic	*and*	R and D budgets	22		
		Society	R and D goals	22		
	particle accelerator	32	criteria for choice	26		
	GeV	32	intrinsic	26		
	ecology	20	extrinsic	27		
	food chains	20	scientific merit	27		
	sulphur dioxide	9	social merit	27		
	carbon dioxide	8	technological merit	27		
	oxidizing agent	8	CERN	29		
	reducing agent	8	Council for Scientific Policy (CSP)	29		
	nitrogen cycle	12, 20	pollution	59		
	Haber-Bosch process	12	nitrogen fixation	62		
	pollution	20	eutrophication	67		
	nitrogen fixation	20	nuclear weapons	69		
			fall-out	70		
			partial test-ban treaty	70		
			nuclear war	71		
			disposal of radioactive wastes	75		
			thermal pollution	77		

* *Any scientific terms used in this Unit but not listed are marked thus † and defined in the glossary.*

Objectives

When you have completed these Units, you should be able to:

I 1 Demonstrate knowledge of the terms and concepts listed in column 3 of Table A by

(a) defining them in your own words, or those used in the Units;
(b) recognizing the best definition or description from a given selection;
(c) matching with one of a series of given definitions.

2 Recall adequately the four levels of decision-making in the institutions of science as outlined in the Units.

3 Recall at least three indices used for measuring the growth of scientific endeavour as a human activity.

4 Recognize, from a given selection of values, the most likely percentage of the GNP devoted to scientific research and development in the following countries: USA, UK, USSR, Japan, W. Germany, Netherlands.

5 Recall three criteria for allocating funds to specific areas of scientific research from limited resources.

6 Recall three categories into which the social effects of science may be divided.

7 Select from a given list of statements those which are relevant to an assessment of the social, political and economic consequences of nitrogen fixation processes.

8 Select from a given list of statements those which are relevant to an assessment of the perils and promises of nuclear energy.

9 Recognize from a selection of given graphs, or by drawing your own, one which exhibits a threshold effect, and one which exhibits no threshold effect.

10 Give a list of biological effects of ionizing radiation, distinguish between those that are acute, long-term and genetic.

II Demonstrate your comprehension of the concepts and principles in the Units by being able to:

1 (a) give at least one example of each; or (b) identify given examples selected from previous Units; or (c) select from a given list of questions those which are typical of activities which could be described as one of the following: basic science, applied science, technology, 'mission-oriented' research.

2 Explain what factors need to be studied in order to illuminate the proposition 'that the kind of science and technology which is carried out is in some sense "chosen" by society'.

3 Précis, indicating the key features relating to social impact, the material presented in the Units concerned with either (a) nitrates or (b) nuclear energy.

4 Distinguish clearly between internal and external criteria for allocating funds for specific areas of scientific research from limited resources.

5 Give, or select from a given list, examples of dependence of modern industry on basic science.

6 Give, or select from a given list, reasons why there are uncertainties in the prediction of biological effects of low doses of ionizing radiation.

7 Give, or select from a given list, reasons why certain fission products (radio-isotopes) constitute a greater biological hazard than others.

III Demonstrate that you can apply your knowledge and comprehension by being able to take and justify a decision, given the available evidence, concerning a proposition to support (or not) a given piece of scientific research in a given situation.

IV Demonstrate your ability to analyse, synthesize and evaluate by:

1 Inferring undue bias or specious argument or other linguistic subterfuges in a communication designed to persuade a research council to support a piece of scientific research.

2 Distinguishing between evidence and hypotheses in a communication justifying a decision taken to support (or not) a given application for a given scientific research grant.

3 In a given scientific development, distinguishing those aspects which relate to the intrinsic logic of the science, to the demands and possibilities of technology and to the extrinsic demands and pressures of society.

4 In a given communication on a technological development, identifying arguments of the 'technological imperative'.

Section 1

33.1 Science and Technology

In Unit 1, we distinguished a set of meanings which are often given to the word science, and asked you to remember them, for we would use them again. It is unlikely you will be able to recall them now; it would be quite a feat! So we repeat them here, for the time has now come when we need to refer to them again.

(i) As the attempt to discover and explain the workings of the world of nature.

(ii) As the application of certain rules of procedure and enquiry.

(iii) As the social institutions within which these activities are carried out.

(iv) As including the whole field of research and development, that is, both science and technology.

(v) As excluding technological developments, embracing instead only pure scientific enquiry typically conducted in certain types of institution such as the university or basic research institute.

From Unit 1 until now, we have been talking about science mainly in the sense of definitions (i) and (ii) above. We have examined how experiments are designed and made, and the rules of scientific procedure applied, and asked you to make some of these applications yourself. But the major part of our time has been occupied, quite properly, with discussing some of the *results* achieved by these scientific methods, in terms of the facts and natural laws (see Unit 1) that science has demonstrated. We have summarized a vast range of facts and laws that the use of scientific methods has provided, making possible explanations of natural phenomena as disparate as the behaviour of gases, the structure of the Earth, the workings of the heart and the pathways of chemical reactions. These 'products' of science are the most up-to-date we could provide; a contemporary account of what is in science's shop-window. To present ideas and results in this way it has been necessary largely to ignore the social and historical context of discovery. Much of the substance of the Course, as presented, has been timeless, and universal. Indeed, it was a deliberate decision on our part to present the material in this form. But you know from Unit 1, from some of the radio programmes and from common sense that, while science is an internally consistent and satisfying body of knowledge, it is also related to the society which sponsors it, and it has developed historically as an organized body of knowledge in a relatively ordered and logical manner.

Science has a history of approximate explanation, faulty hypotheses, half-valid theories, inexplicable data, and unrelated results awaiting the development of a unifying concept which will itself in due course be threatened by newer and inconvenient facts. There is thus a historical sequence to the development of scientific ideas. Certain experiments can only be made or observations collected in the light of the theories they are testing; theories in their turn can only spring out of the data derived from experiment or by the ordered collection of observations.

Recall, from earlier in the Course, examples of such sequences of theories and experiments.

The development of the ideas of the atomic and molecular structure of matter (Units 6–8).

The development of cell theory (Unit 14).

The development of evolutionary theory based on species definition, natural selection and genetics (Units 17, 19, 21).

Continental drift led to the theory of plate tectonics by way of sophisticated oceanographic and seismic techniques (Units 25–6).

The discovery of elementary particles led to SU3 theories which in turn triggered off attempts to find omega-minus particles (Unit 32).

Thus, at one level, we could describe current scientific views and theories as the synthesis of an orderly sequence of observations, experiments and theories which have preceded them over the past 350 years or so of organized scientific endeavour. This would be one way of looking at the development of today's science, in the sense of definitions of (i) and (ii). It is a viewpoint often adopted.

However, a little thought will show it to be at best an oversimplification, for it omits from consideration science in the sense of definitions (iii) and (iv). In Unit 1, we pointed out that modern science and technology were intimately related and that developments in one were linked to developments in the other in a quite specific sense.

It is not merely that certain scientific advances result in the possibilities of certain technological developments, so that, for instance, the development of antibiotics demands a knowledge of theoretical and organic chemistry (Unit 10), that of computers a knowledge of information theory (Radio Unit 18), or that of nuclear weapons a knowledge of Einstein's equation (Unit 4). More than this, it is the case that particular scientific developments can *only* follow on new technologies (which include, you will recall from Unit 1, the instruments of science). For example, Galileo could observe the motions of the moons of Jupiter—a key step in the development of the theory that the Earth moved round the Sun—only after the technological innovation of the telescope (Unit 1). Much of the rest of our Course has shown that science depends on its instrumentation: particle physics is impossible without its accelerators; cell biology without the electron microscope and the ultracentrifuge. Each of these technologies depended on earlier science; each in their turn made further science possible.

It is not part of this Course to examine the reasons why, from the seventeenth century onwards, science and technology developed those links which made possible their subsequent interdependence and growth in Europe. These reasons derive from the transition from a feudal agricultural society to a mercantile industrialized society, which began at about the same time; science and technology contributed to this transition and were themselves in part the products of it. You will have read more of these developments in the historical essay which accompanies this Course and which deliberately sets out to demonstrate these 'social' links of science (by now you should have completed reading it), and in *Science and Society* (Chapters 1–6)* which you were asked in Unit 1 to complete reading before you reached this Unit. Further background reading can be found in *Science and History* (Chapter 14).

We want now to examine some of the consequences of the scientific growth that has occurred since the seventeenth century. The plan of the remaining two Units is as follows:

We begin in section 33.2 by attempting to quantify the scientific growth that has occurred in the last 350 years. We ask what are the characteristics of this growth and whether any regularities within it can be seen. In section 33.3, we assess the state of current science that has resulted from this growth. In section 33.4, we turn to some of the constraints that determine the course of science and examine the various decision-making steps and

* *The material in* Science and Society *itself is* not *regarded as examinable; we do, however, draw on it extensively in the material of this Unit, which* is *examinable.*

processes which ensure that certain sorts of science are done and not others. That such constraints exist is often not immediately apparent to the scientist himself. Nonetheless, by presenting a hierarchical model of the levels at which different sorts of scientific decision are made, we set these problems into their social context. This involves describing the institutions of science and discussing the different levels of decision-making. Four such levels are discussed in detail in section 33.4.

In section 33.5, we turn to the question of the way in which the goals of governments affect the shape of the science they support. By means of a comparative examination of the expenditure on science in several different industrialized countries, we conclude that there are certain regularities in the present way in which governments perceive the role of science and technology within society, and their responsibilities in financing them in order to reach certain specific desired aims. The support of science and technology by government in all industrialized countries represents the social and financial input by society into science and technology. How is this input reflected in what society gets out of science and technology?

What should be the criteria for scientific choice? In section 33.5, we discuss the formulation of one set of such criteria, and in 33.6 invite you to try your hand at evaluating one such choice, that by the British Government of 1968 *not* to support a venture in high-energy physics, the European 300 GeV accelerator.

What are the social effects of investing in scientific research? This question is discussed in general terms in sections 34.1 and 34.2. But to follow it in depth, we need to look at some particular examples. Of the many that could be chosen, we examine in detail two case studies of particular aspects of scientific development:

(a) nitrogen fixation and the subsequent use of nitrates in industry and agriculture;

(b) the development of nuclear energy, both for military and for peaceful purposes, and the related problems of the biological effects of ionizing radiation.

A third case study is provided by the Home Experiment which goes with this Unit—the measurement of the level of sulphur dioxide pollution across the country—which you will have already begun.

But remember, in entering this area of discussion, we are moving from a region of scientific 'facts', which may be verified within the context of the theories to which they relate, to a region where scientific 'objectivity' interacts with social, economic and political factors (33.4). In such areas, you may not agree with conclusions arrived at by us or others whom we quote. Indeed, one purpose of these Units is to encourage the criticism of such conclusions. It is only against this background that we can advance, in section 34.5, to ask the final question of the Course: science and technology for what?

33.2 Scientific Growth

indices of scientific growth

It is obvious that science and technology have grown since the seventeenth century. But can any precise measure be made? A variety of indices may be chosen to try to quantify the scientific growth rate, many of them used in the pioneering studies begun in the nineteen-fifties by the historian of science De Solla Price. It is possible to calculate the number of practising scientists at work, or the percentage of a country's gross national product (GNP)* spent on 'science', or the number of scientific journals in which research work is published, or the total number of pages printed in scientific journals each year. None of these figures properly measures all that might be embraced in that convenient portmanteau word 'science'; on the other hand, all of them clearly measure something to do with the activities of scientists and the scale of their work.

exponential growth

When such measurements are made, they show a striking uniformity in overall pattern; on whatever index is adopted, the activity of 'science' is found to have grown, practically continuously, at an exponential rate since as far back as measurement can be hazarded—say the end of the seventeenth century. 'Exponential growth' means growth at compound interest, so that something is increasing by a fixed percentage of itself each year. Such a form of growth (plotted linearly and semi-logarithmically in *Science and Society*, Fig. 1, p. 5) is fairly common both in biological and social systems. Bacterial colonies grow exponentially, at one point of their growth cycle. So does the human population. So has the economy of industrialized nations over the past one hundred and fifty years or so—the GNP of even a relatively stagnant economy like Britain's on average achieves a growth rate of up to three per cent a year. That science should grow in this way is not altogether surprising, though it is surprising that a period of exponential growth stretching over so long a time-span can be found. That it is also the case for such indices as the number of scientific journals founded each year (*Science and Society*, Fig. 2, p. 6) is at first sight astonishing.

Exponential growth of this sort does have some interesting properties that are very important for appreciating its consequences. One of these is that the quantity which is growing doubles itself over a time-interval of fixed length; if the growth rate is r per cent per year, then the doubling-time is very nearly $70/r$ years. Describing growth by doubling-time is useful for showing its long-term effects; for example, a population increase of 3 per cent per year may not seem large, from year to year; but it produces a doubling of the population in less than a single generation of twenty-five years.

Another property of exponential growth is that it becomes more and more rapid. In fact, the *rate* of growth of an exponentially growing quantity increases exponentially, as you can check for yourself by looking at the numbers 1, 2, 4, 8, 16, 32, ...

** The gross national product is the most commonly used way of measuring the economy of a country. It gives a figure, in money terms, for all the goods and services produced in a given year.*

Number	Increase in Number
1	
2	1
4	2
8	4
16	8
32	16

Another characteristic of exponential growth is that the *increase in the sum* produced in any doubling period is greater than the sum over all previous periods.

Number	Increase in Number	Sum of Numbers	Increase in Sum
1			
2	1	3	2
4	2	7	4
8	4	15	8
16	8	31	16
32	16	63	32

All the quantitative indices of scientific work show a fixed doubling-time of about fifteen years; and this extends backwards over 350 years. Hence, the volume of research done since the end of the Second World War is greater than all of that done previously. The vast majority of scientists who have ever lived are still alive and working today, although this does not necessarily mean that there are more great scientists still living than the collection of such figures as Archimedes, Copernicus, Galileo, Kepler, Boyle, Hooke, Newton and so on.

But this exponential growth of science is of great practical concern, because its rate is so much greater than that of the economy of any nation. Whatever is measured by 'economic growth', it gives some indication of the total resources likely to be available for any particular activity. As a general rule (to which there are some exceptions), industrialized societies do not sustain growth rates of much more than 3 per cent a year, or a doubling-time of about twenty-five years. So, over the past few hundred years, science has gradually come to involve a greater and greater proportion of the total economic resources of industrial countries, and a greater and greater proportion of their total manpower. Thus in Britain (as you will recall from reading *Science and Society*, Chapters 4–6) the cost of doing science, including technology, research and development, rose from a few million pounds a year before the Second World War to nearly one thousand million pounds a year today. As a percentage of the country's GNP, science has risen from a fraction of one per cent to around three per cent. From an activity practised by a few hundreds of enthusiastic amateurs in the seventeenth century, it has increased to a major national activity. Today there are more than 300 000 qualified scientists and engineers in Britain, though not all of them are involved in research, of course.

One can construct arithmetical paradoxes with the growth-rate of science. Assuming it to continue unchecked, it can be shown that by the middle of the next century, every man, woman and child in the country would be a scientist—but before that time could arrive, the science budget would be greater than the GNP and the total mass of the scientific journals produced would exceed the mass of the Earth. Of course, this is not a prediction; it

is a reminder that the present rate of growth of science cannot be sustained indefinitely. And this is only what also occurs in natural systems; biologists have shown how a culture of organisms growing in a confined medium first has an exponential phase of growth, and then, when it becomes constricted, it 'tails off'.

In fact, in the last few years there have been a number of signs that the period of unrestrained scientific growth is coming to an end; in Britain the growth rates have slackened off, whilst in the United States (which spends the vast sum of nearly 20 000 million dollars a year on science) the total sum has even shown a slight decline. The transition from a period of rapid scientific growth to one of little or no growth may present considerable problems in the next few years. You can read more about this in *Science and Society*, pp. 248–53, if you wish.

Nonetheless, the enormous increase in science that has taken place in the industrialized countries since the Second World War has resulted in a situation in which the science budget is almost entirely financed by government in one way or another, even though science is done in many places—universities and research institutes, government research stations and hospital laboratories, industrial laboratories and research associations. Tables 1 and 2 give an indication both of the scale of this spending and where it is actually done. (Do not attempt to remember the details.) In this context, look also at Tables 2 and 3 of *Science and Society* (pp. 124–30). The quantitative change in the scale of scientific activity—from Galileo to CERN, from Spallanzani to molecular biology—has been so great as to suggest that there has been a qualitative change in the nature of the scientific endeavour itself; to what has been called '*big science*' as opposed to the old style string-and-sealing wax of '*little science*'. 'Big science' is done by scientists in teams, working with massive equipment in large research institutes. Work programmes and the development of the institute must be planned years, sometimes decades, ahead, and the huge investment involved in the project must be the result of decisions on the spending of money at government level. Examples of such projects include the 300 GeV accelerator, the US space programme, and the Anglo-French development of the supersonic airliner, Concorde.

big science
little science

Table 1

Finance for research and development, 1961–62, 1964–65, 1966–67, and 1967–68 in the United Kingdom

	1961–62		1964–65		1966–67		1967–68	
	Amount (£m)	Percentage	Amount (£m)	Percentage	Amount (£m)	Percentage	Amount (£m)	Percentage
Sector providing the funds								
Government:								
Defence	245.7	36.7	255.1	32.6	244.5	26.7	225.9	23.9
Civil	110.1	16.4	128.2	16.4	176.7	19.3	202.3	21.4
Research councils	29.2	4.4	43.7	5.6	52.6	5.7	57.1	6.0
Total	385.0	57.5	427.0	54.6	473.8	51.8	485.3	51.3
Universities	1.3	0.2	1.8	0.2	5.0	0.5	5.7	0.6
Public corporations	22.7	3.5	26.8	3.5	35.3	3.8	44.5	4.6
Private industry	243.5	37.0	284.8	36.9	354.0	38.2	360.7	37.5
Overseas	12.0	1.8	20.8	2.7	25.9	2.8	30.3	3.1
Other			16.0	2.1	26.7	2.9	27.8	2.9
Total	664.5	100.0	771.4	100.0	926.3	100.0	962.1	100.0

Source: Department of Education and Science

Table 2

Current expenditure by type of research activity 1967–68 in the United Kingdom

(£ thousand)

	Basic research	Applied research	Develop-ment	Total
Government				
Defence	4 450	15 787	51 721	71 958
Civil	8 872	27 844	38 537	75 253
Research councils	18 894	8 344	113	27 351
Total civil	27 766	36 188	38 650	102 604
Non-government				
Universities	31 000	30 500	—	61 500
Further education establishments	679	768	178	1 625
Public corporations	1 632	17 640	15 152	34 424
Research associations	1 604	7 213	2 834	11 650
Private industry	15 688	96 484	395 213	507 385
Total (exluding non-profit making and other organisations)	50 603	152 605	413 377	616 584
Non-profit making and other organisations	4 936	6 247	1 924	13 107
Total non-government	55 539	158 852	415 301	629 691

Source: Department of Education and Science

33.3 The Problem of Choice

When science is conducted on such a scale, and with such overwhelming possibilities of altering the quality of human life—of even providing the tools for its continuance or destruction—the problem of *what* science is done, how choices are made between different types of research, between spending more on physics or on biology, hospitals or research institutes become of extreme importance. There are neither the resources nor the manpower to do all the science that society might want to do today, any more than there have been at any time in the past. To understand some of the problems of today's science, therefore, we have to begin by looking at how decisions about science are made and what the impact of these decisions is on the community.

We can take these problems of choice and arrange them in an hierarchical order, ranging from the highest level of decision-making, which involves society as a whole, to the lowest level of decision-making, which involves the individual research worker.

Theoretically, at least, society is free to choose whether it will allocate any resources to science at all. More practically, in the real context of an industrial society underpinned by science and technology, the actual question is how much to allocate. At the level of the individual research worker, there are constant decisions to be made, as he selects and rejects skills, techniques and equipment in pursuit of his research strategies. You will have become conscious of some of these yourself as you planned and designed your own experiments at home and in the laboratory during the Summer School. Between these extremes of macro and micro decision-making in science lie a range of intermediate decisions that have to be made to determine which fields of science should be supported. For example, should society back high-energy physics or molecular biology, Earth sciences or electronics, computer science or cosmology? When the broad decision to support a particular field, such as electronics, has been made, there follows the problem of allocating resources to particular laboratories, and to units and individuals within the laboratories. And it is the interplay of all these decisions that eventually determines what science will and will not be done.

Nonetheless, although we have said that these decisions can be arranged in an hierarchical order, as in Figure 1, the divisions themselves are arbitrary, and useful only in so far as they help us understand the decision-making process. Consequently, although we can classify decisions, as Linnaeus did his species, social definitions tend to be rather more fluid than biological definitions, so that the different levels of decision-making interlock, with, for example, particular people playing prominent roles simultaneously at several different levels. However, before we complicate the model we shall examine it as it stands (Fig. 1).

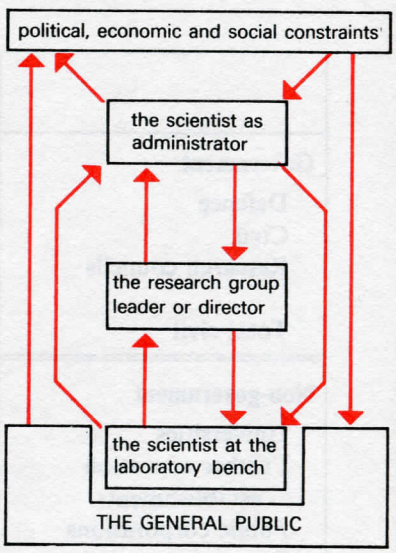

political, economic and social constraints
the scientist as administrator
the research group leader or director
the scientist at the laboratory bench
THE GENERAL PUBLIC

Figure 1

33.3.1 Decision-making at the grass roots: the laboratory bench

In the last analysis—despite the enormous growth in science, so that much of it has become big science, with large teams of scientists working together—the individual scientist still has continuously to make decisions. In some sense, his creativity as a scientist depends on his ability to make the right decisions, to pick his way through a series of complex research options,

decision-making in the laboratory

so that his ability to choose *not* to do the unproductive experiment is as important as his ability to choose the productive one. To take an example from your own experience: in Unit 15 you measured the activity of an enzyme, salivary amylase, at several different temperatures. We left the choices of temperature to you. As you will have observed in making the experiment, an economic experimental strategy would have given you the result you needed with far fewer observations than if you had chosen to make readings at 1° or 5° intervals throughout the entire temperature range. In choosing the best strategy, you were using your creative judgement as a scientist.

To function as a professional creative worker in this way, the scientist has to have a considerable degree of freedom to decide how best to approach his problem. If we compare the scientist's job with that of an assembly-line worker, who *must not* innovate, *must not* make decisions about how to do things (even if we think that this is not the way an ideal society would occupy people's time) then the degree of freedom functionally necessary to the business of being a scientist becomes apparent. It is this inbuilt freedom, alongside the need to achieve work that is accepted by his fellow scientists, giving the successful scientist prestige and recognition, that contribute towards the fascination of science which was so expressively revealed by Professor Ziman in the radio programme of Unit 1.

As Sir Peter Medawar, director of the National Institute for Medical Research, and a Nobel prizewinner for his work on immunology, observes in his essay describing the nature of scientific activity*: 'Good scientists study the most important problems they think they can solve'—there is no point in tackling problems which cannot be approached with the techniques available. To take an example from your own experience: you could not measure optical transmission in the ultra-violet with your colorimeter, and it would have been pointless to have designed experiments which depended on doing so.

But you could participate in an experiment of this kind in the TV programmes of Units 15 and 16.

Consequently, a scientist must aim not only to be technically competent—and to know which problems he thinks he can solve and which he cannot—but he must also be able to decide which of these are scientifically important—that is, to use Ziman's terminology, which rate merely as puzzles and which as problems. Without this crucial ability to see either the most important problems (or, more modestly, reasonably important problems), research is likely to become trivial and to be doomed to 'crawling along the frontiers of knowledge with a hand lens'.

However, to say that science and technology need freedom to innovate is not to say that science proceeds in chaos, hoping for a lucky break. Instead, the research worker operates within a highly formalized set of rules—rules of procedure, evidence and proof—and it is only within these rules that he can select his research problem, and the techniques, apparatus, experiments, hypotheses and theories which will enable him to resolve it. Thus, while luck may play a part, particularly in determining priority of scientific discovery (that is, who publishes the results first and gets the credit), it is the kind of luck which offers opportunities which only the disciplined imagination can perceive and from which it can subsequently profit. A good example of a disciplined imagination at work is the rediscovery of cytochromes by David Keilin, quoted in Unit 15. Keilin describes how in studying the muscles of flies he observed certain pigments and he suspected that they played some part in respiration. The seeing of the pigment and the suspicion of its function constitute the 'luck' and the

* The Art of the Soluble—*recommended background reading for Unit* 1.

'imagination'. The subsequent saga records Keilin's research strategy, which used a minimum number of experiments to demonstrate that the pigmentation could be nothing other than cytochromes; a strategy of economy and elegance. The kind of problem Keilin was tackling is one that belongs to *basic* science. It may be asked how this analysis relates to different problems, to those of applied science (sometimes called mission-oriented science), which uses existing scientific knowledge and applies it to practical problems. Distinctions between the different sorts of science are frequently made. But in some ways the division is too neat. More than one scientist has described how, in his own work, he moves from basic to applied and back to basic work in pursuit of a problem. It has been claimed that there are no divisions in science between basic and applied science; there is only good science and bad science.

33.3.2 The research environment

The kinds of choices the research scientist has to make are determined to a considerable extent by the goals of the scientific institution in which he works—though the capacity of the scientist to do what *he* wants to do *despite* the institution should not be underrated! The basic research institute and the university research laboratory are generally geared towards understanding the natural world; the industrial research laboratory is generally geared towards the goals of the firm, which include productivity and profit maximization. (You will see and hear this discussed in more detail in TV and Radio 34.) In addition there are 'mission-oriented' research institutes which are concerned with specific problems, for example, in Britain, the Government's Water Pollution Laboratory or Building Research Station. Even within such institutions, the divisions may not be as neat, or the goals as well defined, as we have suggested. Scientists in industrial laboratories may 'smuggle in' basic research which fascinates them. A few industrial laboratories specifically commit themselves to encouraging some basic research, whilst there has been in Britain over the last few years a sustained attempt by Government to make university research more commercially and industrially oriented. But despite this, there are differences in the goals of the institutions which result in the exclusion of certain kinds of scientific problem as being 'too applied' (i.e., not concerned with the generation of new knowledge but with the application of existing knowledge to fresh problems), or 'too theoretical' (i.e., the research is insufficiently directed towards solving practical problems, and therefore brings no 'pay-off' for the firm, or for the 'mission-oriented' research institute).

constraints of the research environment

These constraints provided by the research environment limit and focus the choices of scientists within it. Specific research projects can be discussed and evaluated (1) in terms of their quality as scientific projects, and also (2) in terms of their relevance to the goals of the organization. For the most part, such decisions are made by the head of the institute, in consultation with the more senior of the research staff; however, in a few laboratories the management of the research is discussed by all the research staff and the decisions taken collectively. But because science and technology are innovatory—in the sense that they are concerned with *new* knowledge, *new* applications, *new* techniques—the structures for decision-making within the laboratory must be fairly flexible, for fresh ideas must be able to come forward, which would be difficult in a rigid bureaucratic structure. But regardless of the way the decisions are reached, they are in themselves complex. Even if it is possible to identify the most productive research lines and concentrate the laboratory's resources on them in terms both of people and equipment, this will entail stopping less interesting work. Yet in the process it is also necessary to maintain the creative collaboration of scientists who have been personally committed to

those lines of research now labelled 'less interesting'. It should, of course, be emphasized that this somewhat formal model of decision-making is a bit over-simplified. In any actual situation, a good many other factors are likely also to intervene—there may be more representation from outside the laboratory itself, from elsewhere in a firm, or from the general public. Nonetheless, this description summarizes the 'bare bones' of the situation.

As most sciences move irrevocably away from the period when it was possible to work virtually single-handed—requiring very little by way of resources—into the phase of 'big science', this management of research at the laboratory or team level becomes increasingly important, although it *is* still possible to work almost single-handed in some of the less mechanized areas of science—the classification of biological species or of rocks are examples. Many scientific papers today have more than one author, and it is not unknown, in the case of high-energy physics, for an entire research group to be named as authors of one paper. It is also increasingly common for the greatest scientific distinction, the Nobel Prize, to be shared between two or three researchers.

33.3.3 The scientist-administrator

The level of decision-making above that of the industrial institute or laboratory is that in which the claims of different and competing sciences and institutes for resources are weighed in deciding the best mix of investment, both between individual fields (for instance, between physics and biology, or Earth sciences and electronics) and within the fields (that is, which are the best laboratories and scientists to support). In Britain, the allocation is carried out by the five Research Councils, having regard for a general strategy laid out by the Council for Scientific Policy (Fig. 2)*. The five are the Medical Research Council, the Agricultural Research Council, the Science Research Council, the Natural Environment Research Council and the Social Science Research Council. The Councils are served by a civil service secretariat but are themselves manned predominantly by scientists. They are responsible to the appropriate government department, that is the Department of Education and Science, but have a high degree of autonomy.

Research Councils

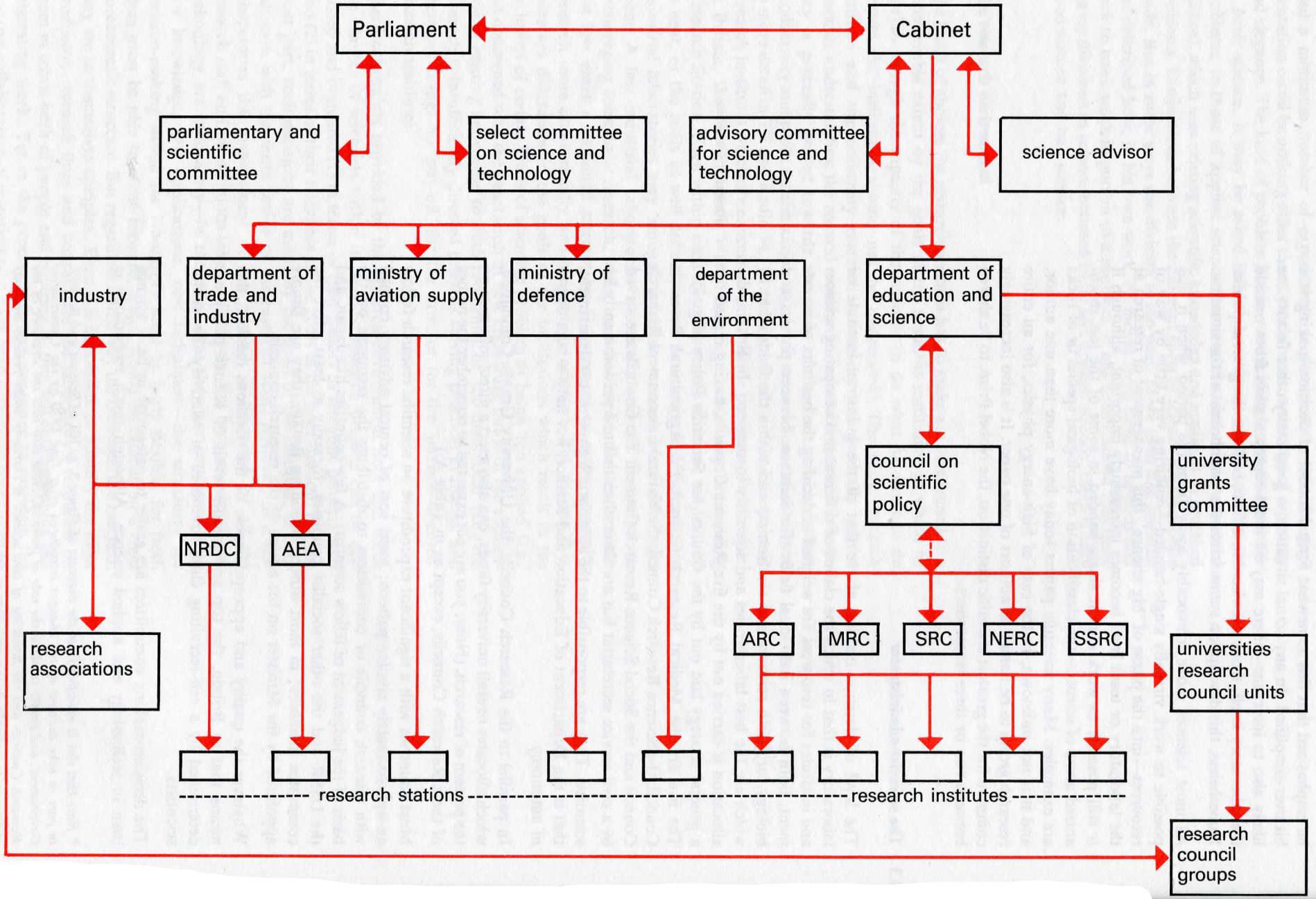
In parallel to the Research Councils, the University Grants Committee, which allocates overall university funds, can also exert a direct influence on the pattern of research. (Note: you are *not* expected to remember the names of these Research Councils, except as in Table A.)

Most countries with a significant expenditure on scientific research follow an approximately similar pattern; some sort of central advisory council with research councils or committees to distribute the resources on the basis of the judgement of fellow scientists. A few countries like Japan, and the USSR and the other socialist countries, formally at least, elect the committee members; in most others, including Britain, they are simply appointed by the Minister on the advice of the research councils.

Whatever the quality and appropriateness of the decisions reached, this means that in Britain, the top and middle levels of science policy are determined by a self-recruiting élite, composed of relatively few senior scientists.

The decision-making committees are easier to categorize in basic science than in technology and applied science. Although much technology is

* *Note that this is modified from the diagram of Figure* 3, *p.* 101 *of* Science and Society, *in part to take account of the changes introduced after June* 1970 *by the Conservative Government, and partly to show the role of industry. Note also that the structure of the Research Councils and the financing of civil science is currently under review, and may change quite radically in the next year or so.*


Parliament
Cabinet
parliamentary and scientific committee
select committee on science and technology
advisory committee for science and technology
science advisor
industry
department of trade and industry
ministry of aviation supply
ministry of defence
department of the environment
department of education and science
council on scientific policy
university grants committee
NRDC
AEA
research associations
ARC
MRC
SRC
NERC
SSRC
universities research council units
research stations
research institutes
research council groups

groups

government-funded in Britain, as you will have observed from Tables 1 and 2, a substantial proportion is not, and much of the Government's money is spent on contract to individual firms. Many of these contracts in recent years have come through the Department of Trade and Industry (once called the Ministry of Technology (see *Science and Society*, pp116–23)). But, in the nature of things, the technological decision-making processes are more complex and less easy to follow than some of those in basic science, which is why we have chosen as a teaching example a decision primarily concerned with basic science.

Even in basic science, though—as with the management of the individual laboratory—the decisions themselves are intrinsically difficult. It is just as difficult at the Research Council level to cut back expenditure in an existing field of science and redirect the resources elsewhere as it is at the laboratory or even at the personal level. The temptation is to distribute small prizes all round, like Lewis Carroll's *Alice in Wonderland*, giving out prizes in a scientific Dodo race. Recently, the Science Research Council has been attempting to 'rationalize' its funding of research fields, by trying to concentrate it at particular universities and research institutes—the so-called 'centres of excellence'. However rational this attempt may have seemed, it ended in vigorous protests from those institutes that were not so classified. This problem of choice (as you will see in the decision-making exercise of section 33.6) is always complex. In the 300 GeV Committee, set up by the Science Research Council, it resulted in open disagreement between the physicists and the chemists present on the committee.

33.3.4 The political level

In the last analysis, decisions on scientific spending are political—particularly today when the massive resources required by science can only be afforded by the State. The basic political question used to be whether the State should support science—and indeed in the mid-nineteenth century there was a vigorous controversy on just this point. In the age of *laissez-faire*, it was firmly believed that for the State to support science was bad for both. However, while it was possible in the nineteenth century to delay the inevitable State support of science, the real question today, for any advanced society based upon the industrial application of science and technology, is not *whether* the State should support science, but *how much* it should do so.

While many of the decisions at the other levels of science can be readily assessed intellectually only by scientists, the overall decisions are much more explicitly political. Choices between detergents or deterrents, schools or roads, new housing or scientific research, are political decisions, that is, they are guided by people's political ideas about the *kind* of society they want and their evaluation of what things (such as more science or less science) are needed to achieve their goals.

To see what political choices are actually made at this hierarchical level, it makes sense to examine the situation not only in Britain but also in those other industrial countries which spend a substantial proportion of their GNP on science. In fact, at the moment, there seems to be a curious consensus both as to how much such a country should spend on science, and on the type of decision-making structures necessary to allocate such spending. Although the Soviet Union and the United States spend rather more than other countries, 3 per cent of GNP has gained acceptance as a desirable target for industrial societies, while 1 per cent has become that of 'third world' countries. But, as we go on to discuss, whereas the total budget calculated as a percentage of GNP may be the same, the *kind* of science a country is getting for its money can vary substantially.

33.4 National Science Policies and Goals

33.4.1 The allocation of resources

R and D expenditure as a percentage of GNP

The most frequently cited single index of scientific activity of any given country is the percentage of GNP that is allocated to research and development (R and D). While it by no means has to follow that the frontiers of knowledge are automatically pushed out by money, the expenditure pattern remains a useful indication of the relative level of resources employed. Even this, however, has certain difficulties, as what is included under the budget heading of 'research and development' varies slightly from country to country. In particular, the Soviet Union calculates R and D expenditure in a different way from the Western Countries. However, comparison in 1962 showed that the USSR was spending some 2.5 per cent of GNP on research and development, although this is probably an underestimate. At the same period the US was spending some 3.1 per cent, Britain 2.2 per cent, and the average for Western Europe including Britain, was some 1.6 per cent. Table 3 shows a more detailed breakdown for the years 1963–65.

Table 3

The level of R and D in selected countries

	Population (millions)	Percentage GNP	$ per capita spent on R and D	Qualified scientists, engineers, and technicians per 10 000 population
USA	193	3.4	110.5	35.8
France	49	1.6	27.1	17.9
Germany	59	1.4	24.6	18.0
Italy	52	0.6	5.7	6.0
Japan	98	1.4	9.3	19.5
Britain	55	2.3	39.8	29.4
Austria	9	0.3	3.8	4.5
Belgium	17	1.0	14.7	16.8
Canada	48	1.1	22.5	12.6
Netherlands	19	1.9	27.2	25.8
Norway	7	0.7	11.5	10.4
Sweden	19	1.5	33.5	21.6

Data from different countries have been given for differing times between 1963–65.

On the whole, there is a broad correlation between the wealth of the country and the size of its research budget, not only in cash terms—such as the 19 000 million dollars spent by the United States during 1967 on research and development, compared with the 4.2 thousand million spent by the whole of Western Europe—but also in terms of the proportion of GNP spent on research and development, which seems to increase with the wealth of the country. Thus, in developing countries, it is rare to find more than 0.2 per cent of GNP committed to research and development.

But, to the extent that American companies, such as the pharmaceutical firms, are finding Europe cheaper to conduct research in, there is also currently a general displacement of research and development funds from the United States towards Europe, which produces a conflicting trend to that suggested by Table 3.

The second most generally applied measurement of the research activity of a country is the percentage of manpower employed in research and development. In the United States in 1962, some 6.2 per cent of the total population were employed on research and development, compared with only 2.9 per cent in Western Europe, including Britain. A generous interpretation of the Soviet research and development estimates (which probably include rather a lot of activities which are not really included as R and D in the W. European or US figures) gives 6.2 per cent for the USSR also. Or, looked at another way, for every one research worker in Germany, France or Belgium there are two in Britain, and four in Russia or the United States. This manpower index, plus the per capita research expenditure, are probably the two most useful indicators of the overall level of research commitment. The gross science budget of the United States is not a valid measure of research activity, as the cost of living, and therefore of carrying out research is much greater in the United States. For example, the economist Christopher Freeman calculated in the early 1960s that to buy the same research resources in the United States as in Britain one needed slightly over $6 to every £1 while the official rate of exchange was then $2.8 to the £1 (of course, the figure may well be different today). In the same way, even within any one country, there is uneven economic development, which makes research dearer or cheaper to conduct in different parts of the country.

percentage of population employed in R and D

33.4.2 The research goals

While the level of total research and development expenditure provides a base line for considering the way in which governments view science, what is even more telling is the allocation of these funds between alternative goals within science, and in particular the split between defence and civil science.

civil research and defence research

Study guide

The discussion which follows contains detailed examples, but you are *not* expected to remember any of these details. If you wish to read more about this topic read *Science and Society*, Chapters 7 and 8.

Thus Japan, which for many years following the Second World War did not carry out any defence research, committed all her research and development resources to civil research. This both contributed to and reflected her commitment to rapid economic expansion. By contrast, in 1963 the United States spent as much as 62 per cent of her total science budget on defence-related items (although, since the Second World War, a proportion of US spending on 'defence' science has been used to fund projects not obviously related to defence, ranging from linguistics to palaeomagnetism. However, a recent (1970) change in the law in the United States, is likely to put an end to this state of affairs, which has been in part a consequence of competition for 'prestige' between the various branches of the US defence forces). As Table 4 shows, both France and Britain were similarly heavily committed to defence research in 1963,

spending 45 per cent and 40 per cent of their total science budget respectively, followed by Sweden with 34 per cent. The item which pushes up the US defence programme beyond all others is space research, which, since October 1957 and the first Russian sputnik, has received massive political and economic support. Both the United States and Britain have long-standing atomic programmes, and during 1963–65 spent some 7 per cent of their budgets on atomic research, while France and Sweden, with research programmes which have been expanded only relatively recently, spent as much as 22 per cent and 27 per cent of their budgets on the same item.

Table 4

The allocation of R and D budgets in 1963 to different research goals for several countries

	Atomic	Space	Defence	Total of Atomic, Space and Defence	Civil		Per cent
					Economically motivated	Welfare and miscellaneous	
U.S.	7	21	34	62	28	10	100
France	22	1	22	45	41	14	100
Germany	8	1	8	17	62	21	100
Italy	15	1	5	21	63	16	100
Japan	—	—	—	—	73	27	100
U.K.	7	—	33	40	51	9	100
Austria	11	—	1	12	62	26	100
Belgium	—	—	—	4	82	14	100
Canada	10	1	15	26	51	23	100
Norway	7	—	7	14	56	39	100
Netherlands	—	—	—	5	70	25	100
Sweden	27	—	7	34	50	16	100

The research goals described in Table 4 as 'welfare' and 'economically motivated' are correspondingly depressed by these high defence expenditures. The United States, the richest society, spent $110 on research per head of population per year. Although only 10 per cent of this sum was allocated to welfare objectives, this still meant some $11 per head—more than any other country (although here again one should note that European money buys more research per 'dollar' than American, so the difference appears magnified). However, for Britain, which spent $39 per head on research, 9 per cent on welfare meant only $3.8 a head. France, spending 45 per cent of her research budget on defence, reduced her welfare expenditure to slightly over $3 a head. The Netherlands by contrast, with a lower research and development expenditure per capita ($27.2) than the UK, spent less on defence and could thus allocate $6.8 to welfare. Similarly, Western Germany with a population size very similar to Britain's, and with a modest defence research budget (17 per cent), spent almost $5 a head on welfare.

In assessing these figures, of course, it should be noted that they are 'snapshots' of particular years, those for which the international comparisons are available. Long-term trends may change the proportion spent by any one country in any sector. Thus a declining proportion of UK and US budgets has gone to defence research in the last five years, an increasing proportion of France's and Japan's. Japan and France are now increasing their effort in space research, the United States reducing hers. Only the general relations between goals and funding need concern us here.

The distribution of the research budget, even for the richest society, is therefore of key importance in determining the real inputs into the constructive aspects of science as against the destructive ones. Consideration simply of the overall level of research and development can therefore be very misleading, particularly for the medium-sized country. A high total research expenditure, which might not unreasonably be expected to be associated with rapid economic growth, appears very much more modest when pared down by excluding defence expenditure, most of which, despite the possibilities of 'spin-off', is concerned with the destructive aspects of science. Thus, it may produce a correspondingly modest economic growth —as has been the case with Britain, for example.

33.4.3 A synthesis of policies?

national science policies

For most of the nations we have considered, the goals of science policy have become similar: a combination of economic growth and preservation of national independence. Economic growth means a tendency towards a technologically-oriented science; preservation of national independence means both the fostering of national scientific enterprise, more or less conspicuously identified, and, of course, spending on military science. Preservation of national independence in science may take many forms: the stars-and-stripes painted on the side of the first manned spacecraft to the moon; the paper given in French at an international meeting; the insistence that the originators of cybernetics and television were Russian; the national specialization in electronics by the Dutch; or the argument over whether the Anglo-French supersonic passenger plane should be Concord or Concorde.

It seems as if, in the years since the Second World War, as science policies have become crystallized, these goals for science have become predominant in many countries, including Britain, the USA and the USSR. The convergence of science policies in these countries makes possible the fact, for instance, that scientific 'competitions' (like the 'race to the moon') between the USA and USSR are an accepted part of international relations. Even within a country like Britain, convergence of goals has occurred as well. Thus, both Labour and Conservative Governments have pursued science policies which, in varying degrees, have had both economic and military goals. Indeed, the existence of such goals for science is now recognized internationally, and they have become so 'obvious' as to be beyond question. Yet it is proper to look more critically at the nature of society's goals for science.

33.5 Criteria for Scientific Choice

The whole of the preceding part of this Unit has really been a scene-setting operation: an attempt to indicate the constraints under which such goals are selected. Such a debate is not 'merely' academic, for it concerns, as you will see in the case studies that follow, real issues with real social consequences. Although the debate about the goals of science stretches back at least as far as Francis Bacon, whose seventeenth-century scientific utopias were accounts of how one might hope to see science organized in an ideal society, for a contemporary analysis of the issues we need go no further back than the early 1960s, when a challenging attempt to set 'criteria for scientific choice' was made by Alvin Weinberg, an American physicist and director of a large complex of nuclear laboratories which had been set up during the Second World War for the atomic bomb programme. Weinberg's analysis precipitated a debate through the 1960s in which scientists of international status, deeply involved in the administration of science, took an active part, and there is good evidence that the ideas voiced in that debate have indeed been influential in helping scientists, administrators and politicians analyse the varying considerations involved in scientific choice. The criteria may not have been original, and their assumptions are open to dispute. Nonetheless, they produce a framework within which it is possible to assess decision-making in science. We include here a brief account of Weinberg's criteria; a more detailed discussion will be found in *Science and Society*, Chapter 11, pp. 210–18 (black-page reading).

33.5.1 Weinberg's criteria

Weinberg makes an immediate distinction between two kinds of criteria; these he terms *intrinsic* and *extrinsic*. The former derive from inside the scientific field and, roughly speaking, answer the question: 'How well is the science done?' The latter derive from outside the immediate scientific field and partly from outside science altogether. The intrinsic criteria are essentially the same as the reasons for allocating resources to a particular musician, painter or sculptor, and at this level science has no greater claim on resources than any other cultural activity. Any special claim to the massive resources now demanded by 'big science' has therefore to come from outside science, and may well involve social, political, defence and economic considerations.

intrinsic and extrinsic criteria for scientific choice

Intrinsic criteria

Two intrinsic criteria can be recognized:

1 Is the field ripe for exploitation?

2 Are the scientists in the field really expert?

Both of these questions are answerable only by experts who know intimately the field in question and who know the people personally (recall from Radio 17 Sir Lawrence Bragg's account of the way in which the work on the structure of myoglobin by Max Perutz was financed by the Medical Research Council). Answering them properly is the function of the various expert committees of the research councils.

Extrinsic criteria

Three extrinsic criteria can be recognized:

1 technological merit;

2 scientific merit;

3 social merit.

These criteria need more detailed discussion. We may expand them as follows:

technological merit

1 *Technological merit*, in terms of the technological capability to do things, is fairly obvious. Once society has decided that a certain technological end is worthwhile, it must support the necessary scientific research to achieve that end. (The question of whether the technological aim is itself useful can be similarly analysed in terms of its intrinsic qualities and in extrinsic terms of its social implications.)

scientific merit

2 *Scientific merit* is more difficult to define, but basically the scientific merit of a specific field can be judged best by scientists working in immediately adjacent fields, as it is the relevance and unifying effect of new discoveries to them which signals a work of high scientific merit.

For example, in the field of molecular biology, the elucidation of the structure of DNA by Watson, Crick and Wilkins, and the more recent work by Nirenberg and Ochoa defining the way in which the triplets of nucleic acid bases determine specific amino acids in proteins, both had the effect of relating areas of genetics, cytology and microbiology (Unit 17). The field with the greatest scientific merit in the Weinberg analysis is that which contributes most heavily to and illuminates most brightly its neighbouring disciplines. This work thus has, on these criteria, high scientific merit. Later work, which may analyse in much greater detail the base sequence of a particular transfer-RNA, may have considerably less scientific merit, in this sense, because its relevance to surrounding areas of science is less.

social merit

3 *Social merit* is measured by the relevance of the project to human welfare and human values. Here one is immediately in an area of conflicting values and conflicting political views. The H-bomb is at the same moment passionately argued for, as the best aid to the preservation of peace, and also against, as the best aid to the destruction of the human species. Nonetheless, it is possible to analyse the different threads in any argument concerning social merit in terms of basic needs such as food, new sources of energy etc. This kind of social cost-benefit analysis is inevitably tentative and more readily susceptible to verbal than quantitative analysis. At times, these separate threads amongst the criteria of social merit become so entangled and so lengthy, trailing off into the remote future, that reasonable speculation moves near to the art of the science fiction writer. However, when one remembers some of the successes of science fiction prediction—Jules Vernes's submarines and rockets and H. G. Well's flying machines and atomic bombs—probably ridiculed, if enjoyed, by their scientific contemporaries—one can be forgiven if one feels a little unnerved by Ray Bradbury's or John Wyndham's speculations as to the development of telepathic people, or Isaac Asimov's vision of a man-inhabited Galactic system.

What we are saying is that it really is frequently too difficult to assess the full social merit behind a fundamental research project. Consequently sometimes the only honest answer to the question 'What is the use of this particular piece of science?' may well be to reply along with Michael Faraday, in the form of counter-question, 'What's the use of a baby?'

Thus it can be argued that, according to the external criteria proposed by Weinberg, the work of such physicists as Planck, Einstein, Schrödinger, Heisenberg, de Broglie and Dirac in the period 1910–30 may well have appeared to have relatively low merit, for although the work was of great importance to certain problems in physics, it seemed at that point to have little or no relevance to anything at all outside theoretical physics—and perhaps philosophy. Yet this work is the basis of the quantum mechanics, which has transformed not only all branches of science but industry and society as well!

Before turning to the next section and examining how these criteria may be applied in practice do Self-Assessment Questions 1–7, *which relate to sections* 33.1–5.

33.6 The 300 GeV Accelerator Project: a Decision-making Kit

This 'decision-making kit' is your 'Home Experiment' for Unit 33. In it, we ask you to analyse a particular decision made by the British Government in 1968—the one not to support a recommendation made by its scientific advisory committees, the Council for Scientific Policy and the Science Research Council, to participate in a joint European venture to finance a giant particle accelerator, the 300 GeV machine (see Unit 32 for relevant discussion of such accelerators). Note that we are not asking you to evaluate the *rightness* or *wrongness* of the decision (which has anyhow been altered by a subsequent government and changing scientific and political circumstances). Since the time of the 1968 decision studied here, a new, cheaper project has been proposed by CERN scientists, and accepted by the British and other governments. (See the Broadcast Notes for TV 33.) Here, however, we are asking you to study the methods by which the 1968 decision was made.

To do this, we will present you with a set of government and committee reports, statements by eminent scientists, etc. for examination and evaluation. In reading them, you will be studying some of the raw material of decision-making, on which any analysis must be based. The recommended method of proceeding is as follows. Read through the material, in the order presented here, once fairly rapidly. Then go through it again, more slowly, and this time answer the *SAQs* in it. Finally, attempt the *CMA*. Do not go on to Unit 34 until you have completed this assignment.

33.6.1 Contents of the kit

The kit contains the following components:

(a) a statement of the background to the CERN accelerator and an historical account of the sequence of events involved in the actual decision;

(b) extracts from a report by the British Advisory Council on Scientific Policy (the forerunner of the present Council for Scientific Policy) on 'criteria for international co-operation in science';

(c) extracts from a report by the Council for Scientific Policy and Science Research Council, who were asked to advise the Government on the accelerator proposal, including a minority report;

(d) a press release describing the Government's official response to the report;

(e) some views on the merits of the Government's decision, expressed by some eminent British physicists, and published in the scientific weekly magazine, *Nature*;

(f) a discussion of the case against the accelerator by an Earth scientist, published in the political weekly, *The Spectator*.

(**Note:** all extracts are given as they appeared in the original, except that we have occasionally shortened the text. Minor shortenings are indicated thus (. . .) and major ones by a break in the text thus (* * * *). Where major omissions of substance have been made, we summarize the contents of the omitted section.)

33.6.2 Background information on CERN

Read first the discussion of the organization of CERN itself given in your set book, *Science and Society*, pp. 189–94. Do not try to remember the names of the scientists involved. This is set into a historical perspective by the event chart of Figure 3 (facing p. 32).

33.6.3 The 300 GeV accelerator proposal

A general account of the history of the British decision on the 300 GeV machine is given in *Science and Society*, Chapter 12, pp. 233–9. Read this before proceeding further. Note that in that book, the discussion of the CERN decision follows a chapter on the Weinberg criteria for choice (Chapter 11) and a detailed discussion of another government decision concerning the establishment of a World Health Organization (WHO) Research Centre at Edinburgh ('Operation Megamouse') (Chapter 12, pp. 219–32). Both these accounts form useful ancillary material to this discussion, and should be considered as black-page reading.

33.6.4 The general policy statement on international collaboration

We now turn to the first piece of experimental evidence offered. This is an extract from the 1961–62 report of the Advisory Council for Scientific Policy. (ACSP) which lays down the 'guidelines' on which the government should judge its collaboration in international scientific activities. The ACSP was, like the present Council for Scientific Policy, an advisory body of eminent scientists and industrialists, appointed by the government and staffed by a small full-time secretariat. The main responsibility of the ACSP was to review the country's scientific 'state of health' and make regular reports to the government of the day, which was not, of course, bound to act upon them. Specific policy items would be referred to the ACSP for consideration.

Extracts from the Annual Report of the Advisory Council on Scientific Policy 1961–1962 (HMSO Cmnd 1920) Guidelines for International Co-operation in Science

1. At the end of last year the Minister for Science drew attention to the growing numbers of proposals for international co-operation in science. He invited us to consider the whole question of international scientific activities, and to advise on the issues of policy to which they give rise.

2. International scientific co-operation takes many different forms. It is convenient to distinguish the following main types:

(a) Co-operation, mainly consultative in character, arising in connection with the activities of international organisations which have a much wider general purpose (e.g. UNO, the O.E.C.D. and NATO).*

(b) Collaborative scientific research projects in which a programme of research, within a defined field, is co-ordinated internationally, but is carried out and financed nationally.

(c) Centralised international schemes, in which research facilities are provided and controlled internationally. * * * *

* *United Nations Organization; Organization for Economic Co-operation and Development; North Atlantic Treaty Organization.*—Ed.

11. The United Kingdom is participating in four of these schemes one of which (ESRO) is still in the formative stage. The estimated expenditure on them is:

	Estimated expenditure during 1962–1967		Estimated expenditure in 1962–1963	
	Total £m.	U.K. £m.	Total £m.	U.K. £m.
European Organisation for Nuclear Research (CERN)	41.4	10.4	6.8	1.7
European Space Research Organisation (ESRO)*	30.3	7.6	0.4	0.1
The Halden reactor experiment*	1.0	0.14	0.4	0.04
The Dragon reactor project*	18.0	7.2	5.4	2.3

12. These schemes differ widely in type from each other, but all of them involve centralisation on a regional basis. A centralised scheme enables the larger contributors to participate fully in a scientific venture which nationally they might not be able to afford. Those participating countries with smaller financial resources are enabled to play valuable parts, and the growth of science in these countries is advanced. Through a centralised scheme, the calls on high grade scientific man-power are shared, and a participating country whose financial contribution to a scheme is small might in fact be supplying a scientific leader of the highest quality.

13. The Council attach importance to the principle that where a centralised international scheme provides facilities for research which is fundamental in character, national teams—working in their own universities—should have a major share in the use of the facilities provided. This principle has already been established for CERN and ESRO. It is no doubt necessary that a large institution like CERN must also have an international staff which itself carries out a good research programme. It should be noted, however, that proper use of very advanced apparatus provided internationally is not possible by member countries without a substantial measure of activity within the countries themselves. Thus the existence of CERN does not in any way obviate the need for a national effort in nuclear physics, and may indeed stimulate its expansion. In our view it is important to ensure that national research teams from universities can engage in the very advanced fields of research which are opened up by the provision of international facilities such as those at CERN. . . .

14. Where the purpose of a centralised international project is applied research or development leading in time to commercial exploitation, different considerations arise. In the Dragon reactor project, the patents and knowhow are normally confined to the participating countries and the ultimate objective is economic. The decision whether or not to join such projects must therefore depend on economic and technological considerations rather than on the need to broaden the horizons of world science.

15. It is proposals for schemes involving centralised international co-operation which raise the most difficult issues. Schemes of this kind are costly. The principle normally adopted is that the participants share the cost in proportion to their gross national products. The United Kingdom's normal contributions amount to about 25 per cent in Western European regional schemes. Such contributions would not, of course, include expenditure incurred by individual member countries on work in preparation for, or in follow-up of, actual experiments done, with the use of the facilities. Any proposal for an expensive scientific scheme—on an international basis—must therefore raise the question whether, from our national standpoint, the enterprise is worth the cost involved for a heavy contributor. In reaching decisions in matters of this sort it is important that strictly scientific considerations are given full weight.

* *These projects need not concern you in detail. You can read about ESRO, the European Space Research Organization if you wish in* Science and Society, *pp.* 194–7.—Ed.

Conclusion

16. The development of international co-operation in science is, in principle, desirable. But the extent to which organised international co-operation is necessary must depend upon the circumstances of each case. In advanced fields of scientific research, there is massive interchange of knowledge and ideas between scientists in different countries. This takes place spontaneously. There is also much physical interchange of scientific research workers and teachers between countries either as visitors or for longer terms. The arrangements for financing these exchanges are complex and do not seem to be as widely understood as is desirable. In our view one of the most useful ways of assisting international co-operation in science would be to review and improve the existing arrangements for international exchange of scientists.

17. While the Council consider that the international collaborative schemes in which the United Kingdom has so far participated, have, for the most part, produced stimulating and worthwhile results, it is not possible to claim that any and every international scientific collaborative arrangement necessarily has merit simply because it is international. Each scheme needs to be considered on its scientific merits. Proposals for centralised schemes are even more difficult to judge. Where the cost of equipment is very high such schemes may be the only means by which the scientists of most countries can enter certain fields of research, but it may still be the case that participation may cost more than it is worth—particularly for a country with a high contribution. There are limitations to the costs which a country can incur on scientific activities and domestic scientific efforts may have to be limited if costly centralised international scientific projects increase greatly in number. The maintenance of reasonable balance between national and centralised international activities, and a close relationship between them is, in the Council's view, of great importance.

18. In some forms of international co-operation there is an element of assistance to smaller countries, or a general political or economic objective, such as European integration or the strengthening of the European economy, which may be served by participation. While due weight must be given to these factors, we believe that it is mistaken to suppose that it is preferable to resort to international activities whenever possible, simply because it is politically desirable to extend the area of international co-operation. In the end the political value of co-operation will be proportionate to the extent to which there are real scientific advantages for all the participants. As the Minister for Science suggested to us, it should not be supposed that international co-operation is a substitute for national excellence.

Before going on to the next document, consider the following questions in the light of the ACSP report, then check your answers against those on p. 33. These questions will test your comprehension and ability to apply the arguments advanced by the ACSP.

1 Which of the following are selected in the Report as MAIN TYPES of international scientific co-operation?

Schemes which are:

(a) Centralized and international.

(b) Based on collective responsibility for social outcomes.

(c) Based on full and associate contributions.

(d) Based mainly on consultation about activities of international organizations of wide purpose.

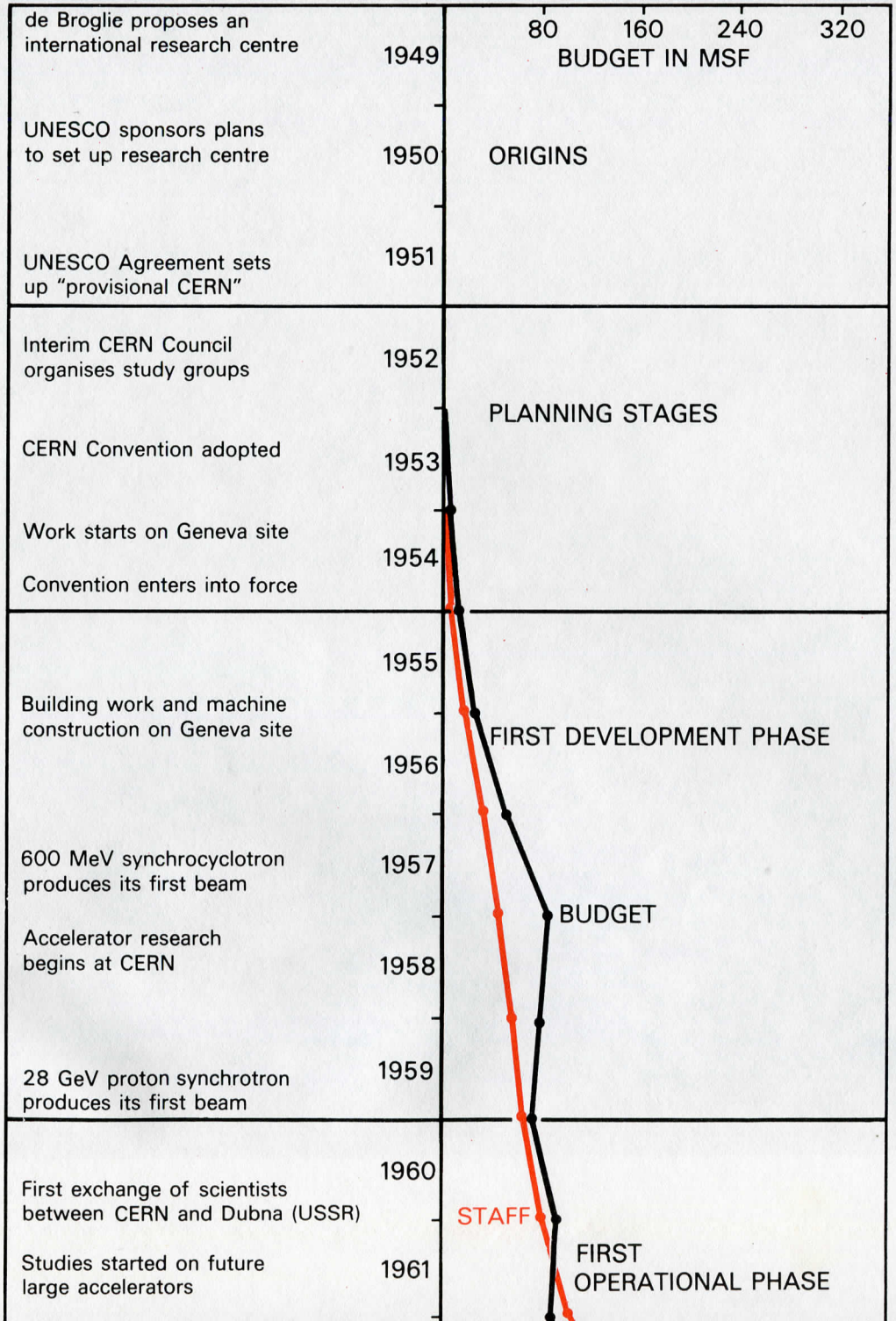
(e) Based on collaboration in projects which are otherwise carried out and financed nationally.

(f) Based on convenient geographical groupings.

(g) Primarily concerned with applied and developmental research.

(h) Concerned primarily with political and economic objectives.

2 Imagine that you are a member of the ACSP Secretariat of an imaginary country, Western Uravia (WU) and that you are required to interpret the spirit of the principles laid down in the section of the 1961/2 Annual


de Broglie proposes an international research centre
1949
UNESCO sponsors plans to set up research centre
1950
UNESCO Agreement sets up "provisional CERN"
1951
Interim CERN Council organises study groups
1952
CERN Convention adopted
1953
Work starts on Geneva site
1954
Convention enters into force
Building work and machine construction on Geneva site
1955
1956
600 MeV synchrocyclotron produces its first beam
1957
Accelerator research begins at CERN
1958
28 GeV proton synchrotron produces its first beam
1959
First exchange of scientists between CERN and Dubna (USSR)
1960
Studies started on future large accelerators
1961
80
160
240
320
BUDGET IN MSF
ORIGINS
PLANNING STAGES
FIRST DEVELOPMENT PHASE
BUDGET
STAFF
FIRST OPERATIONAL PHASE

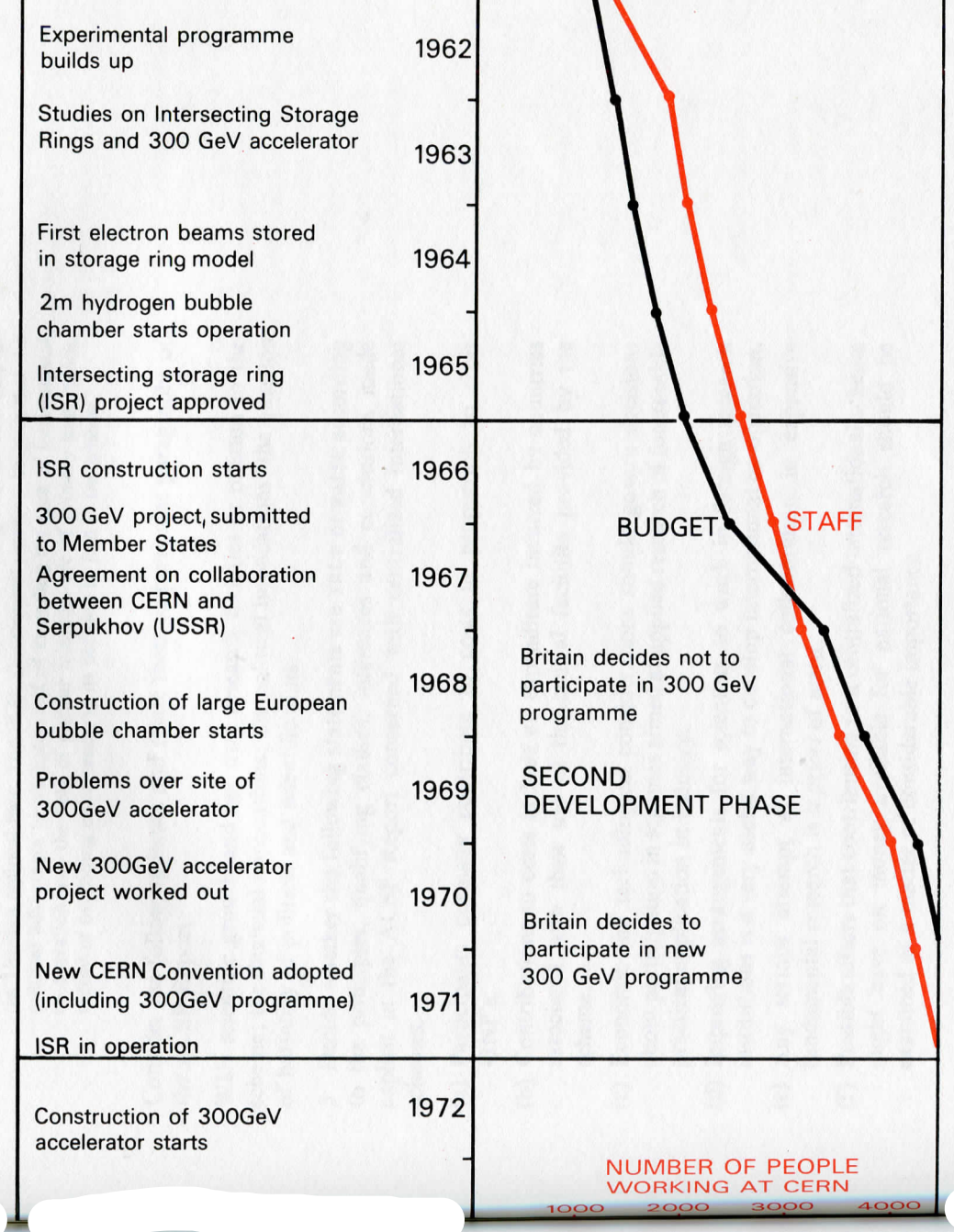


Figure 3 The history of CERN: an event chart

Report concerned with international co-operation in science. Analyse the following statement of the case for WUs participation in a new, imaginary research venture, and note the main points you would include in a commentary prepared for the Council.

Statement of the case for Western Uravia's participation in GLIMMA

Western Uravia is a small country of limited resources, but one which has reached an advanced state of industrialization. It has decided to participate in research into the nature of the Gristellian Layer of the inner nuclear miasma—an investigation of fundamental scientific importance. W.U. has no scientists at present working in this field, nor does it intend to mount any projects within its university or National Institute on this subject. It considers that its contribution to the costs of the international scheme (which would in any case not be proportional to the W.U. gross national product) would entitle its scientists to monitor progress on the Gristellian Layer research, which may lead to discoveries which could well strengthen the economy of the Uravian political bloc. The W.U. Government sincerely believes that the political advantages to all concerned of extending the area of international co-operation into the field of nuclear miasmics are of primary importance, indeed of overriding importance, in its decision to join in the scheme.

Consider the following issues and relate them to particular paragraphs of the ACSP Report:

WUs scientific growth and her own research facilities in relation to the scheme; the financial implications; the political implications; the question of harmony of political and scientific aims.

3 Decide whether the following statements are TRUE or FALSE according to the principles, qualifying clauses, inferences and conclusions made explicit in the ACSP Report concerned with centralized international schemes.

(a) Participants normally contribute to costs in proportion to their GNP's.

(b) Contributions to costs include all expenditure incurred by countries associated with their use of the central facilities provided by the scheme.

(c) Economic and technological considerations should govern decisions about participation in schemes aimed at applied research of foreseeable practical application in industry.

(d) Improving arrangements for scientists to work in foreign research institutions is a very useful way to develop international co-operation.

(e) Any serious attempt at international collaboration in expensive fundamental research is *a priori* of merit.

(f) Possible effects that contributing to a centralized international scheme might have on money available for national research should be examined as a matter of considerable importance.

Answers

1 The following are selected in the report: (a), (d), (e).

2 (Numbers in parentheses refer to paragraphs in the ACSP Report.)

It is difficult to see how WU can gain acceptable advantage from or play any valuable part in GLIMMA:

A Its scientific growth will not obviously be advanced (12) nor can it supply high quality scientists as leaders for the scheme (12).

B WU does not intend to use the facilities for research being set up in the scheme (13) nor does it intend to set up its own support research in nuclear miasmics (13).

C The contribution proposed by WU is not proportional to its GNP—this is unusual (15). Perhaps this indicates some misunderstanding.

D The Council, in its Report, specifically rejects political desirability for extending the area of international co-operation as an overriding factor in a decision to participate in a centralized international scheme (18).

E Participation by contribution to costs only, in order to monitor progress for possible economic advantages hardly accords with the spirit of the ACSP principles.

3 (a) True, (b) False, (c) True, (d) True, (e) False, (f) True.

33.6.5 The Council for Scientific Policy and Science Research Council's Report

In 1967, the Council for Scientific Policy (CSP) was asked to assess the proposal that Britain contribute to the proposed European 300 GeV machine, which would come into operation in 1977 and would cost about £180 million altogether (on 1967 estimates).

The Science Research Council (SRC) is, in a sense, a subordinate of the Council for Scientific Policy. It first referred the proposal to its own special subcommittee dealing with nuclear physics, which came down in favour of the project. The full SRC (Table 5), which contains representatives of many sciences, then reviewed the project and presented a report to the CSP which (with the exceptions discussed below) recommended that Britain join the project. The CSP in its turn set up a special committee to consider the implications of spending the amount of money required if Britain were to participate, for the general welfare of science in Britain.

Table 5

Membership of the SRC in 1967

Sir Harry Melville, K.C.B., F.R.S., Chairman, Science Research Council, and Principal of Queen Mary College, London.	Nuclear physicist
Dr. A. Caress, Director (retired), Imperial Chemical Industries.	Physicist and industrial scientist
Dr. D. G. Christopherson, O.B.E., F.R.S., Vice-Chancellor, University of Durham.	Mechanical engineer
Dr. S. C. Curran, F.R.S., Vice-Chancellor and Principal, University of Strathclyde.	Nuclear physicist
Professor G. C. Drew, Professor of Psychology, University College, London.	Psychologist
Dr. M. R. Gavin, C.B.E., Principal, Chelsea College of Science and Technology.	Electronic engineer
The Rt. Hon. The Earl of Halsbury, F.R.S.E., President, National Institute of Industrial Psychology.	Industrial scientist
Professor Sir Ewart Jones, F.R.S., Waynflete Professor of Chemistry, University of Oxford.	Organic chemist
Professor Sir Bernard Lovell, O.B.E., F.R.S., Professor of Physics and Director of Nuffield Laboratories, University of Manchester.	Radio astronomer
Dr. K. Mather, C.B.E., F.R.S., Vice-Chancellor, University of Southampton.	Geneticist
Professor Sir Ronald Nyholm, F.R.S., Professor of Chemistry, University College, London.	Inorganic chemist
Professor C. F. Powell, F.R.S., Pro-Vice-Chancellor and Henry Overton Wills Professor, Director of H. H. Wills Physics Laboratory, University of Bristol.	Nuclear physicist
Dr. J. E. Smith, F.R.S., Director, Marine Biological Association Laboratory, Plymouth.	Zoologist

The extracts which follow are drawn from the SRC report to the CSP, and the CSP's subsequent report to the Minister, the Secretary of State for Education and Science. The full report was published in 1968 (HMSO Cmnd 3503) under the title *The Proposed 300 GeV Accelerator*.

Before assessing it, note the membership of the SRC at that time (Table 5, do not try to remember the names).

Extracts from the CSP/SRC Report

(a) The Background

The success of the C.E.R.N. laboratory, and its American and Russian counterparts, has generated further requirements for accelerators capable of producing particles of greater energy than hitherto achieved. In the Soviet Union, there is an accelerator of 70 GeV under construction at Serpukhov. The United States has initiated a definitive design of a proposed 200 GeV proton accelerator (expected to cost $240 m. excluding supporting equipment) which it is proposed will be situated in Weston, Illinois. At a later date, this might be upgraded to as much as 400 GeV. * * * *

European, including British, nuclear physicists have now proposed a new and much larger nuclear accelerator. This machine would produce protons, the nuclei of hydrogen atoms, accelerated to an energy of 300 GeV (that is, the energy acquired by an acceleration of 300 000 000 000 volts) and would promote high energy nuclear research: an activity which explores the internal constitution of the particles of an atomic nucleus and represents a significant frontier of scientific enquiry. The machine would not come into operation until 1977, by which time costs would on present estimates be 1 776 m. Swiss Francs shared among the participating nations. Whether the machine should go ahead depends of course on there being sufficient European nations willing to participate. The United Kingdom has been invited to participate in this project and C.E.R.N. has asked the British Government for an early decision.

The proposal cannot be considered by itself, but rather as part of the plan for all high energy nuclear physics, both national and international. This in turn must be balanced against the long-term developments of all pure and applied science in this country; a problem made more difficult by the necessarily long development time of the 300 GeV machine.

The Government therefore sought advice from the Science Research Council and the Council for Scientific Policy. The Science Research Council unanimously accepted the scientific merit of the project, and by a substantial majority recommended participation, subject to certain safeguards concerning the cost of the project, and the need to protect other sciences for which that Research Council is responsible. *Two members of the S.R.C. dissented from this latter recommendation* (our italics—Course Team).

(b) The Case for the 300 GeV Machine

Using the existing machines, a whole series of fundamental discoveries has been made, regularities have been observed in the so-called elementary particles taking part in the reactions studied, and there is every promise that future work in this subject, extended to higher energies, will elucidate fundamental laws of nature, whose existence at present are only a matter of speculation. Thus, work in this field is fundamental science. It has at present no more immediate application to commercial exploitation than had the work of Lavoisier, Faraday and Rutherford in the 18th, 19th and 20th centuries. The discoveries of these workers led nonetheless to the development of major industries around 50 years later (sometimes less, sometimes more). The experiments proposed with the 300 GeV machine are probably just as

fundamental and may perhaps lead in time to equally important industries. It is true that a few major scientific advances made between 50 and 100 years ago have so far led to no direct commercial applications. Such cases are rare: there is therefore a presumption that experiments in this branch of physics may well lead in 50 years or more to direct commercial application, the nature of which cannot be surmised at present, though it is pertinent that the reaction energies involved are about ten to a hundred thousand times greater than those involved in nuclear structure physics or nuclear fission. But, from the point of view of direct commercial exploitation within the next generation or so, any possible benefit should be ignored. Work on such a project must, therefore, sharply be distinguished from present day work (say) on nuclear reactors or semi-conductors. . . .

Unlike the work of the earlier fundamental scientists, however, this work is extremely expensive. Thus, the British contribution to C.E.R.N. in 1967–68 will be £4.82 m. and to national facilities £10.01 m. in addition there being the cost of work done at Universities. Including this university element, the total annual national expenditure on nuclear physics (including perhaps 10 per cent. on nuclear structure) at present is over £17 m.

Thus, decisions as to whether to proceed further in this one field of research involve an expenditure which is a substantial fraction (rather less than 7 per cent.) of the total expenditure by the Government on civil research and development. The sums involved, although large, are not completely disparate with funds allocated to other research purposes. Thus a recent survey showed that Government expenditure on all biological research in 1964–65 was £49.7 m. or 25 per cent. of the then total. Nevertheless this figure included all Government supported medical and agricultural research (£22.6 m. and £16.9 m. respectively) much of which had very direct potential application.

If we in the U.K. are to continue as leaders in this area of fundamental research, a system of national and European accelerators must be planned as central facilities for University researchers, keeping in perspective the likely new machines in the U.S., the U.S.S.R. and Japan. Indeed, there is already talk of a 1 000 GeV machine, perhaps to be built as an intercontinental venture. This is for the future: the matter we have to advise upon now is whether viewed in this wider perspective, the U.K. should participate in the proposal for a 300 GeV European Proton Synchroton to begin operating in 1977. Several European sites have been proposed for the 300 GeV machine, including one in the U.K. (at Mundford in Norfolk). A selection of these sites will be made on technical grounds after the countries concerned have signified whether they wish to participate. . . .

In deciding whether or not to participate in this project, and thereby to remain in this field of research, there is one further important factor that must be stressed, Science is indivisible: concepts arising in this field, though unlikely to lead to rapid direct applications, may in ten to twenty years permeate the whole of other fields of science, just as the concepts of quantum mechanics now permeate the whole of physics and chemistry. Thus it is very important to ensure that a proportion of those trained in physics research will be conversant with the concepts and techniques arising first in high energy research but not exclusively associated with that one field. The researchers may well need this knowledge in other employment in 20 years time. Such a transfer of knowledge can, in our judgement, occur effectively only if the U.K. and the rest of Europe as well continue in this field at an appropriate level. * * * *

(The report goes on to explain that sharing in the US machine would be no substitute for Europe having its own.)

. . . Concentration on a theoretical high energy physics programme, to the exclusion of experimental studies, would also be in no way a substitute: we believe that theoretical studies in this, as in so many disciplines, flourish best in relatively close proximity to experimental

work. For these reasons, as well as the need to support general scientific morale, we must consider if we can afford *not* to participate in the proposal. . . .

The proposal has been studied in detail by the Nuclear Physics Board of the Science Research Council. . . . We . . . accept that the scientific merits of the work proposed are of the very highest order: we understand that the Nuclear Physics Board assigns the highest priority to this project relative to other Nuclear Physics projects, either existing or proposed, and we understand too, that the S.R.C. has endorsed the scientific merits of the case and has by a substantial majority recommended that the project be adopted subject to a number of safeguards. Even with the adjustments that the S.R.C. has made to their plans in order to accommodate this machine, the project will, if approved, require growth rates in the S.R.C. vote (budget—*Ed.*) for some years over and above those which might seem likely for the Science vote as a whole on the basis of forward extrapolation of present trends. Moreover, a decision to participate will involve the U.K. in expenditure as a continuing commitment for thirty years or more ahead. It, therefore becomes important to examine the effect of this proposal on the balance of U.K. scientific effort in the foreseeable future in terms of resources both of money and men, and indeed, its impact upon the pattern of university scientific research as a whole in this country. In addition, we have been asked to consider the wider implications of this proposal; the possible benefits to British and European advanced technology, and the economic implications, including the possible benefit of siting the machine at home or abroad. * * * *

The report goes on to consider costs, for which it had the benefit of advice from two independent economists. We have plotted the proposed costs as estimated in the report in Figure 4.

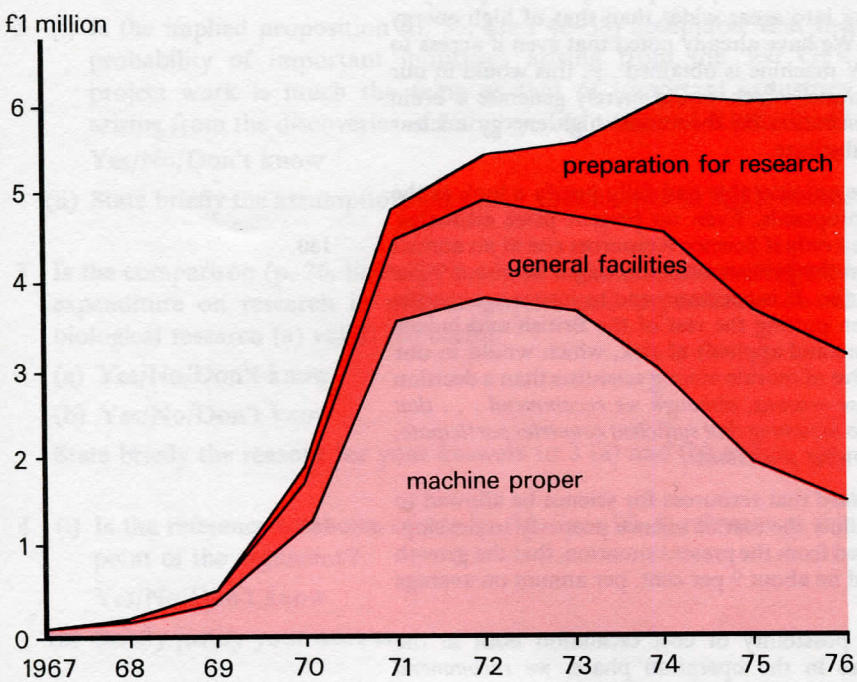


Figure 4 U.K. contributions to the proposed 300 GeV machine.

The British contribution to the costs was to be around 25 per cent of the total. The Report continues by considering the problem of cost escalation and decides that the figures presented are realistic and should not escalate unreasonably.

It compares the cost of supporting the 300 GeV machine with current and estimated costs of other physics (Table 6, p. 38).

On this basis, it concludes that the extra cost of the proposal can be contained in the overall science budget of the SRC.

Nor, the report concludes, would the project represent an excessive drain of qualified physicists or engineers.

Table 6

National cost of high energy physics (1967 prices)

Item	Cost £ × 10^6	
	1967–8	1977–8
300 GeV	—	6.15
Rest of C.E.R.N.	4.82	9.47
British Physics Laboratories	10.01	12.85
Other	2.82	5.70
Total	17.70	34.17

Whilst there would be some scientific benefits if the British (Mundford) site were chosen, it would make, perhaps surprisingly, little difference to the economics of participation.

Finally, the report concludes . . .

Conclusions and Recommendations

We are convinced that this project is of great and fundamental scientific importance and its adoption is essential if the U.K. is to continue as part of a viable European high energy nuclear physics programme. If we do not enter the project, high energy physics would wither away over the next 15 years with the consequent penalty to the quality of trained manpower reaching into areas wider than that of high energy nuclear physics alone. . . . We have already noted that even if access to the United States' 200 GeV machine is obtained . . . this would in our view be a very poor substitute, which would merely generate a brain drain. Nor would a concentration on theoretical high energy nuclear physics be in any way a substitute.

The costs of the project are considerable and fully justify a look at the wider implication of the proposals. Even on present price estimates, the project could be financed only if Science Resources rise at an annual average which judging from the present situation might be about 9 per cent. for the next decade or so. It is necessary too to insure against the possibility of cost escalation putting the rest of the British and indeed European science (both pure and applied) at risk, which would in our view be even more destructive of morale among scientists than a decision not to participate. *For these reasons, although we recommend . . . that we enter the project, we do so assuming that sufficient countries participate, and also subject to the following provisions:*

(i) *assurances can be obtained* that resources for science be allowed to rise at a rate sufficient to allow the rest of science properly to develop. This would suggest, as judged from the present situation, that the growth rate for Science votes would be about 9 per cent. per annum on average for a decade or so, *and*

(ii) bearing in mind the possibility of cost escalation both in the construction and still more in the operation phase, *we recommend the following three safeguards*:

(a) limitation of the construction and operation costs of the machine and ancillary equipment by prior international agreement;

(b) deferring commitment upon operation and equipment costs until construction costs are clearly defined;

(c) meeting any increase in costs during the construction phase by corresponding economies in the Nuclear Physics Budget, . . .

Insofar as it is possible to judge, the proposed machine has been carefully designed, using well-understood principles. Even so, the machine is intended to produce protons of more than ten times the energy and twenty times the intensity of anything previously attained, and the design committee expresses reservations about whether the proton intensity can be attained. . . .

Although there is a strong scientific advantage, and a balance of payments advantage, there is no nett economic advantage, and indeed there might be a nett cost in having the machine situated in this country, since the site proposed is in an area which is likely to enjoy continued full employment. . . . On balance, therefore, we believe that no additional inducement should be offered to secure a U.K. site. . . .

It appears that the manpower requirements of the machine can be met without undue difficulty. . . .

The recommendations made in the last three paragraphs should do much to stimulate a flow of useful ideas into British technology, should we enter the project. But the major justification rests in the scientific merits of the case. Our financial recommendations bear this in mind, and at the same time ensure that if, as we recommend, the proposal is adopted, it should not put the development of other branches of U.K. science at risk.

M. M. Swann* (*Chairman of the Working Group*).

Before going further, check your comprehension and ability to interpret the SRC and CSP reports by answering the following questions. Then check your answers against those on p. 40.

1 (i) Is the argument (p. 35, lines 43–6) involving comparison with the work of Lavoisier, Faraday and Rutherford a fair one?

Yes/No/Don't know

(ii) How strong do you consider this argument?
Very strong/fairly strong/not very strong/not strong at all.

(iii) Briefly state the reasons for your answer to (ii).

2 (i) Is the implied proposition (p. 35, lines 46–58) acceptable that the probability of important industries arising from the 300 GeV project work is much the same as that of important industries arising from the discoveries of Faraday, Lavoisier and Rutherford?

Yes/No/Don't know

(ii) State briefly the assumptions on which your answer to 2(i) is based.

3 Is the comparison (p. 36, lines 70–9) which is made between proposed expenditure on research in nuclear physics and expenditure on all biological research (a) valid; (b) useful.

(a) Yes/No/Don't know

(b) Yes/No/Don't know

State briefly the reasons for your answers to 3 (a) and (b) above.

4 (i) Is the reference to choice of site (p. 35, lines 90–4) relevant at this point of the argument?

Yes/No/Don't know

(ii) Briefly justify your answer.

5 From what you have just read, would you expect high-energy physics in the UK to decline if the European 300 GeV project went ahead with British participation?

* *Professor of Biology, Principal and Vice-Chancellor of the University of Edinburgh, Chairman of the Working Group on the Implications of the Proposed 300 GeV Accelerator.* —Ed.

6 According to the Science Research Council, British participation in the European 300 GeV machine would mean:

(a) direct commercially applicable results;

(b) an expansion of high-energy physics research in the UK;

(c) a 10 per cent share in the cost of the machine;

(d) a transfer of the appropriate knowledge gained to other fields of physics and the rest of science;

(e) a 9 per cent increase in the science research budget over the next 10 years;

(f) a 9 per cent increase in the science research budget per annum over the next 10 years.

Which of these?

7 Make a list of those points arising in the SRC report recommending British participation in the 300 GeV, which, in your opinion were the most convincing arguments in favour of Britain taking part in the venture.

Answers

1 (i) Yes, it is fair.

(ii) We would say 'not very strong' or 'not strong at all'.

(iii) The argument appears to be non-specific and somewhat negative. It does not give support to the proposal for a 300 GeV machine in any particular way—it could apply equally well to any important fundamental research project for which no immediate application can be perceived. It is somewhat negative because it is an argument for not rejecting any project on the grounds of lack of immediate applications.

2 (i) We would say, in the way that the argument was made in the report, no.

(ii) There are two hidden assumptions behind the argument which may not be justifiable.

(a) that 300 GeV can be attained (some room for doubt about this is mentioned later in the report);

(b) that discoveries will be made of such fundamental importance as may well give rise to industries later on.

Now, the comparison is made with Faraday *et al. after* they had *made* important discoveries, not when they were fitting out their laboratories to start new major projects. It is probably possible to find a few scientists of some renown in the nineteenth century who attracted support but subsequently made no discoveries of fundamental importance. The message of the proposition is one of hopeful optimism only, and is not one which helps much in deciding whether or not to spend millions of pounds.

3 We would answer 'Don't know' to (a), because it is not clear what precisely the comparison is meant to show. If, as stated, it is to show that 'the sums involved, although large, are not completely disparate with funds allocated to other research purposes' then the comparison has a kind of validity; but we would then have to consider it useless (i.e. 'No' for (b)). If, on the other hand, 'other research purposes' is to be interpreted as paralleling one part (nuclear physics) of one major field (physics) then 'all biological research' as a comparator is invalid ('No' to (a) above). If it is invalid, then it is presumably useless ('No' to

(b) above). It really is a confusing piece of argument—as the writers of the report doubtless suspected when they wrote the qualifying statement commencing 'Nevertheless this figure included . . .'

4 (i) We are inclined to say 'No'—i.e. site is irrelevant to argument at this point in the report.

(ii) the mention of site was preceded by mention of machines likely in the US, the USSR and Japan. This suggests that European centralized facilities make sense in the context of continental co-operative endeavours in nuclear physics. But the actual site in Europe does not help to make the decision whether the UK is to participate unless (a) one or more particular sites (e.g. at Mundford) have great advantages for the UK and (b) this (or these) particular site(s) is highly likely to be chosen. Neither of these points is discussed here—so the introduction of site at this point seems to be a bit of a red herring.

5 No—it is indicated (p. 36, lines 103–6) that member countries would need to maintain similar national activities in order to gain maximum benefit from the European project.

6 (d) and perhaps (b). (f) is a *prerequisite* for participation, not a consequence (see p. 38, lines 149–52).

7 Now ask yourself whether these points also show technological and social merit?

33.6.6 The Minority Report

The reports of the CSP and SRC were, however, unique in that they also contain a dissenting minority report, by Professor Sir Ewart Jones and Professor Sir Ronald Nyholm, which read, in full, as follows:

> We recognize that a good case on purely scientific grounds, has been made for proceeding with this project. But we are also acutely aware that there are other scientific fields which, cultivated and nurtured as nuclear physics has been in recent years, would yield still richer harvests. Some of these are of no less scientific interest and have much greater potentialities for benefiting mankind. In several of these fields we are leading the world, we should be able to offer generous support where such ability is demonstrated, but this we cannot afford to do.
>
> Our participation in this project means that for the next ten years the Science Research Council expenditure on a single branch of physics will continue to consume more than 40 per cent. of the funds which seem likely to be available. Thus the Council's intention gradually to reduce the proportion of its resources going to nuclear physics will be completely frustrated. We are convinced that to continue to spend such substantial sums in this direction is not in the national interest and that many scientists in this country, if they are properly appraised of the situation, will view the prospect with dismay. Can we expect them calmly to accept a slowing down of their activities whilst we go ahead with a huge project which will directly benefit only two or three hundred academic physicists?
>
> We cannot reconcile embarking upon this massive new commitment with our present unsatisfactory and worsening situation. Can high energy nuclear physics justly claim to be of such overwhelming merit and importance? We should urgently be seeking opportunities of investing comparable, and if possible larger, sums in projects which offer some prospect of material advantage to the community and which at the same time serve to train useful scientists and technologists.
>
> E. R. H. Jones.
> R. S. Nyholm.

Question

The dissenting minority report of the SRC was based upon:

(a) the high cost of the project;

(b) its questionable scientific merit;

(c) the bias towards high-energy physics in the research budget;

(d) an unwillingness to enter into international projects.

Which of these?

Answer (See the margin of page 44.)

33.6.7 The political response

Nonetheless, despite the dissenting views, the recommendations of the CSP were in favour of British participation. Their report was published in January 1968. In evaluating the recommendation, the Government clearly had to take into account not merely the arguments advanced by the CSP but the political situation, which included its assessment of the economic situation at the time, other priorities for government spending, the political advantages accruing to Britain's bid to join the Common Market if the project were to be accepted. . . . We make no attempt to be comprehensive in such a list of factors; for the purpose of this examination they are only marginally relevant. The point is that the decision had moved from the level of the scientist-administrators to the political level. In July 1968, the Department of Education and Science issued the following press statement:

> At the Council for Scientific Policy meeting on July 26, 1968 the Secretary of State for Education and Science, the Rt. Hon. Edward Short, at the invitation of the Council, explained the reasons for the Government's decision not to participate in the proposed European 300 GeV accelerator project. Professor B. H. Flowers (the Chairman of the Science Research Council), and Professor D. H. Wilkinson, Professor Sir Ewart Jones, and Professor F. Hoyle, representing the three Boards of the Science Research Council, were also present.
>
> The Secretary of State expressed his regret that the Government had been unable to accept the advice of the Science Research Council and the Council for Scientific Policy that the accelerator project should be undertaken subject to certain provisions about the future growth of science resources generally. The main reason for the Government's decision was that, in view of its other financial commitments—including obligations overseas which other C.E.R.N. members did not bear—the country could not afford this new commitment. Moreover, once the necessary international treaty had been signed, there could in practice be no withdrawal. Although the project had been carefully costed by those proposing it, the Government had to take into consideration the possibility that costs would escalate—as had happened with other major international projects. The resources required for the project extended over a much longer period of time than that for which overall resources had been allocated to the Research Councils.
>
> The Government had also taken into consideration that there was no short or medium term prospect of economic benefit from so costly a scheme, and that so far there was little movement into industry of the skilled scientific engineering and technical manpower trained by participation in research in high energy physics.
>
> The Science Research Council had put forward revised proposals after the publication of their Nuclear Physcis Board report on the proposed accelerator. These new proposals would have enabled them both to pay for joining the project and to reduce substantially the proportion of their resources allocated to Nuclear Physics by the future closing of the

major national facilities for high energy physics at Rutherford and Daresbury. But this would have provided adequate resources for British nuclear physicists only if the accelerator were sited in the United Kingdom, which the Government regarded as unlikely in view of the low preliminary rating given by C.E.R.N. to the proposed Norfolk site. Moreover, even this new proposal assumed a continued substantial growth of total resources available to the Science Research Council over ten or more years, and in practice it would be difficult to close successful national laboratories in order to finance a new international project, even in the unlikely event of it having been sited in the U.K.

The Secretary of State assured the Council that the decision in no way altered the understanding that the Government did not interfere in the exercise of the Research Councils' own judgement on the allocation of resources allocated to them. This was their responsibility, and he had no intention of questioning their scientific judgement.

It was no part of the policy of the Government to discourage other European countries from going ahead with the present or a modified scheme. The Secretary of State agreed to join in further discussions with the Council for Scientific Policy later in 1968 on the general question of international scientific co-operation in Europe.

Now do the following questions, checking your answers against those on p. 49.

Question 1

The primary reason for Government rejection of the Research Council's recommendations was concerned with:

(a) damage to morale of scientists;

(b) need to discourage other countries from supporting the proposals;

(c) lack of adequate funds in the UK to support the project;

(d) too little promise of direct application of results.

Question 2

'The Secretary of State assured the Council that the decision in no way altered the understanding that the Government did not interfere in the exercise of the Research Council's own judgement on the allocation of resources allocated to them.'

What is the implication of this statement in the context of the particular discussion of the 300 GeV accelerator?

(a) That this instance is a very rare special case of interference which would not be taken as a precedent for more frequent interference.

(b) That the Research Councils are recommending allocation of resources not in fact allocated to them.

(c) That the Research Council's role is only to exercise scientific judgement about projects.

Question 3

Which of the following arguments, used by the Research Council, does the Government find to be not very convincing?

(a) That the field of research is one of fundamental science.

(b) That the cost of participation would be high.

(c) That costs would not escalate unreasonably.

(d) That the UK must participate in the scheme if its scientists are to remain in the field.

(e) That major industries are likely to arise from the results in 50 years or so.

(f) That UK physicists and engineers would transfer their knowledge gained from participation into other employment.

(g) That, on balance, no inducement should be offered to secure a UK site.

(h) That the growth rate of the SRC budget needed for participation was not likely to endanger support for other research.

Question 4

In the press statement there is a reminder of the limits of Research Councils' responsibilities, not mentioned in Questions 1–3 above. What is it?

Answer to the question at the top o
p. 42.

(a) and (c)

33.6.8 The views of some physicists

Following the government's decision, the chairman of the Science Research Council, the physicist Professor B. (now Sir Brian) Flowers, and a number of other leading British physicists, were asked by the weekly magazine *Nature* for their views on the project (*Nature* **219**, 1968, pp. 15–17).

The following are extracts from some of them:

Professor B. M. Flowers

> As a nuclear physicist myself, I deeply regret the decision . . . I have stated that British nuclear physicists considered the 300 GeV project their first priority and were prepared to endure considerable restrictions on their national programme in order to participate in the new laboratory. In our final strenuous efforts to secure participation we were prepared . . . actually to reduce the size of the British nuclear physics community. We assumed that our contribution to the staff of the new laboratory would come primarily and voluntarily from the existing staff of our two national laboratories. This would have led automatically to a position in which one or other of our accelerators would have had to be closed down before the end of its scientifically useful life. We were prepared for other unpalatable measures. In short, we were willing fully to enter into the 300 GeV project, while at the same time substantially reducing the proportion of funds devoted in total to nuclear physics. I hope this council (C.E.R.N.—*Ed.*) will now understand what we meant when we said . . . that this project was our top priority. In the event we have been spared some of the consequences of our own proposals, but we wish it were otherwise.
>
> So, what of the future? I firmly believe that European high energy physics is strong enough to survive one adverse decision. Scientifically there is no doubt of the merit of the project, and technically it is well conceived. This is not in question, as you have already heard. At the risk of seeming impertinent, I must therefore say . . . that I sincerely hope that some way will be found to go ahead without us, and without a long delay. It will not be the first time after all!
>
> It will remain the policy of British nuclear physicists to continue to press our Government to enter the project if, as I hope, it proceeds. It may be that our circumstances will soon improve; it may be that attitudes will change. I cannot for myself believe that in the long run the UK will remain outside. In that profound belief our physicists will continue to play whatever part they can to help, and will try to avoid taking any action which would make it more difficult for us to join in the future.
>
> Finally, may I say that although this has been entirely a personal statement it was shown to the members of the Science Research

Council, of which I am chairman, at their meeting yesterday. Between them they represent a broad spectrum of science and technology. They wished to place on record, and they wished me to say so here, that my statement has their unanimous support, in every detail.

Professor Sir Bernard Lovell (*radio astronomer*)

As chairman of the Astronomy, Space and Radio Board of the Science Research Council, I have regarded the discussions on the 300 GeV accelerator with some anxiety. . . .

. . . I view the decision with the utmost dismay, for two reasons. First, an entire branch of research in physics of the greatest importance and significance will now inevitably decay relative to world standards. Secondly, it seems to me that, on a vital scientific issue, the Government has taken a decision against the advice of the SRC, on political grounds and with a false assessment of the economic consequences. If the argument is that the country can only engage in large scientific projects which will show immediate benefits to the economy, then this makes nonsense of the whole concept of the pursuit of contemporary scientific research.

This decision, coming from a government which has placed so much emphasis on the future of science and technology, is quite bewildering. It is hard to retain faith in pronouncements about the desire for European technical and scientific collaboration. Worst of all, it raises for the first time a most vital issue of principle as between the political body and its scientific advisers which must cause many of us to give deep thought to our future action.

Professor A. R. Bishop (*nuclear physicist*)

The decision to withdraw British participation in the building of a European 300 GeV accelerator for research in high energy physics will have consequences reaching far beyond the immediate threat to a great international project. It raises doubts in the minds of those scientists who have contributed liberally of their intellectual energies to the exhaustive study of the project, of the utility of such an immense effort when their unanimous advice is ignored. The Council for Scientific Policy, the Science Research Council and the Science Advisory Committee to the Cabinet all favoured the scheme. From whom else in the country is it reasonable to expect sound advice on a coherent policy for the continuing finance of work in pure science? It could well be that future historians will single out such decisions as the markers of a new era of mental stagnation, the Dark Ages of the twentieth and twenty-first centuries. What is threatened with extinction when the needs of pure science are lost sight of is the continuance of a human adventure in thought which in the past century alone has wrought more change than happened in all previous times. The extraordinary technological expansion of recent history, which ironically with its topical emphasis on cost effectiveness in investment is the main reason for the disputed decision, took place only because of a fresh attitude of mind which was less cultivated by previous civilizations, themselves in any case already adorned with valuable technologies. This revolutionary viewpoint was the pursuit of knowledge for its own sake, that is without immediately predictable tangible reward. The substance on which technology draws its inspiration for development is the body of knowledge constituted and enlarged by activity in pure science. Stop that enlargement and technology will ultimately stagnate.

Of course the new project is an expensive one, which is why no single European nation can go it alone. But the British contribution was to be found partially by the phasing out of existing domestic facilities. Plans for improving these do exist, but the remarkable fact is that the majority of high energy physicists were agreed to substantial sacrifices in that direction in favour of the international project. Some reserve is felt, however, about the extent of that sacrifice by those nuclear physicists working in nuclear structure research. Nuclear structure physics is the study of the properties of nuclei, and high energy physics the study of the properties of sub-nuclear particles. It is fashionable to say in the preamble to proposals for a high energy machine, to justify the expenditure of public money, that understanding the sub-nuclear

particles is a prerequisite to understanding the structure of nuclei. It is true that it might help, but in much the same way as knowledge of the Schrödinger equation helps the chemist to understand the structure of matter. He still needs his laboratories to solve the practical problems which in principle are 'understood'.

Nuclear structure research is carried out principally by university teams with means that are modest in comparison with high energy accelerators but expensive when compared with the apparatus of chemistry, biology, non-nuclear physics and other scientific disciplines. The machines invented by the nuclear structure physicist, however, are, within a decade or two, the advanced tools of workers in those other sciences, and the same pattern can be expected in the future. In this country about 10 per cent. of the budget for nuclear physics is devoted to nuclear structure work, compared with the proportion maintained by other nuclear powers of about 35 per cent. Here again the British effort is outstripped by the developments elsewhere, even when the return on investment is calculable with greater precision in furthering the ends of nuclear structure research and of other sciences. Thus the new electron linear accelerator at Glasgow takes its place on a world scale after projects constructed or under construction in France, Italy, Germany, Japan, Canada, and the United States. The proportion of 10 per cent. of the nuclear physics budget is too low to permit even the planning of an accelerator for producing beams of pi-mesons for nuclear structure studies, and places in doubt the construction of the next generation of electrostatic generators for similar purposes.

Professor E. H. S. Burhop (*nuclear physicist*)

The decision of the British Government against participation in the new 300 GeV high energy accelerator in Europe has spread bewilderment and a sense of let-down among my younger colleagues working in high energy physics. Research students are questioning the wisdom of continuing in the field while the malaise extends also to more experienced physicists who are beginning to probe round in other directions. I believe the most urgent immediate need is for a getting together of physicists to discuss the possibility of reversing the decision and the measures necessary to prevent a disastrous decline in morale which, if allowed to develop, would make it difficult to utilize fully even our available facilities, and could lead eventually to the virtual disappearance of a serious UK contribution to research in high energy physics.

To my mind, the decision represents another victory for the philistines who evaluate the significance of scientific research in terms only of short-term returns. Admittedly we have had to face a daunting problem in this country in relation to the effective industrial application of scientific discovery. But sufficient people have got the message. Everybody is saying it, from the President of the Royal Society downwards. There is danger of an over-reaction. It is much easier to make the case with the general public (and with the Government) for short-term mission-oriented research. The case for long-term basic research is never won but has to be fought for stubbornly and patiently the whole time.

Many committees and sub-committees of scientists assessed and re-assessed the case for the 300 GeV accelerator. Rarely, if ever, before has a scientific project been worked over so thoroughly. In the end there was virtual unanimity in favour of UK participation and this covered scientists of all disciplines. The overriding of their advice must make many of the scientists concerned conclude their time would have been better spent in the more rewarding atmosphere of their laboratories.

The Government claimed to have been concerned about an imbalance between high energy physics and other sciences. But high energy physics needs big facilities or cannot be pursued at all. The same arguments will be available to stop expansion in other fields of big science. Since more branches of science will increasingly in the future require very large facilities for their development, the present threat to high energy physics is ultimately a threat to all science. It is true that Government has a clear responsibility to watch carefully the rise of expenditure in all spheres, but one would not have thought the present level of expenditure on basic research (0.3 per cent. of the GNP) was yet at a level that could give cause for concern in a technologically oriented society.

One must hope that the other western European governments will show a better appreciation of priorities so that western Europe will get its new accelerator laboratory despite the British decision on non-participation. British participation may then eventually become possible when more enlightened men are charged with the guidance of our destinies at Westminster. Our present Government has continually paid lip-service to the role of science and technology in modern Britain and especially to European scientific and technological co-operation. Is it too much to hope that even at this late hour it may at last match its words with appropriate action and reverse this misguided decision?

33.6.9 Another voice of dissent

Not all scientists were against the decision, though. Apart from the dissenting minority report of 33.6.6, here is another, voiced by an Earth scientist, Dr. Peter J. Smith (geophysicist), in an article in the *Spectator* two years later, when a modified version of the project was being proposed.

Spectator, 11 July 1970

. . . The decision to go ahead with the project now would still be wrong for precisely the same reason that it would have been wrong in 1968—because the consequences for the future of the scientific effort in this country have not been properly thought out. In 1967 the Nuclear Physics Board of the Science Research Council (SRC) investigated the question of the European accelerator and produced a majority report in its favour. This was hardly surprising, for the board comprises mostly nuclear physicists. But the really important point was that the two chemists on the board—Sir Ewart Jones and Sir Ronald Nyholm—dissented. And they did so mainly on the grounds that it would have meant over 40 per cent. of the SRC budgets going to one branch of science—high energy physics, represented by perhaps a couple of hundred people—an unacceptable distortion in the light of requests for funds from other fields. The fact that most of the scientists concerned were willing to countenance this distortion without first trying to determine its effect must throw grave doubts on the ability of the scientific community to manage its own affairs properly. It may well be true that the concentration of resources into one small branch of science is entirely justified; but it says little for the objectivity of scientists that they are apparently not willing to recommend a thorough investigation of the point.

Science policy in Britain has never, of course, been more than a string of isolated *ad hoc* decisions—a state of affairs which worked reasonably well as long as money flowed relatively freely. But the inevitable has already happened. The growth rate of scientific budgets characteristic of the 1950s slowed drastically during the following decades. Scientists are beginning to discover rather belatedly, that the rational allocation of limited resources is a problem with which they must rapidly come to terms.

It is rather ironic that the nuclear physicists should be first to experience the shock, for it is fair to say that they are the only begetters of the most blatant, and successful, confidence trick perpetrated upon society in the last quarter of a century. I agree that scientists and indeed the whole of society have reason to be grateful to the nuclear physicists. Prior to the last war the scientific community was still comparatively small: and although the principle of government support had been established several decades before, science was regarded worthy of such support mainly because of its intrinsic cultural and intellectual merits. But the war changed all that. The intense effort put into the development of the science and technology necessary to produce the atomic bomb, amongst other things, proved once and for all to government that science could lead very quickly to severely practical results and hence, if used correctly, improve the physical lot of mankind.

But the scientists, to their eternal discredit, wove wondrous patterns around public naivety in this matter. They soon learned that the mere suggestion of practical benefit impressed governments far more than intellectual values. As a result, money poured into all branches of science. Even the most esoteric of scientific disciplines found they were

> able to expand at a quite remarkable rate in the financial backwash from projects, nuclear physics especially, that had proved themselves. And most scientists were quite happy with this state of affairs and content to shield their eyes to the intellectual dishonesty which made the cultural justification for science (albeit on a reduced scale) take second place to the material.
>
> In trading upon their past reputation nuclear physicists have developed this type of dishonesty into a fine art. Nuclear physics and its progeny are now as esoteric as the study of mediaeval Swahili. The basic scientific framework which made possible the hydrogen bomb and the nuclear power station was complete at least a decade ago; yet ever since nuclear physicists have managed to pull the wool over politicians' eyes in somehow insinuating that today's intellectual ideas are tomorrow's exports. None of this is to say that nuclear physics is no longer worth doing but only that nuclear physics should have taken its place among the rest of pure science in the hierarchy of priorities. . . .

The television programme of this Unit explores these views more fully. Do not attempt the CMA until you have seen the television programme. But meanwhile, you might like to ask yourselves the following questions. (We provide no answers!)

1 Do you think that, from what you have read, in the case of the 300 GeV decision, the SRC and CSP behaved responsibly
   (a) to scientific research;
   (b) to the community in general?

2 Did the Government behave responsibly in this case
   (a) to scientific research;
   (b) to the community in general?

3 Having read the various comments made by scientists in reaction to the Government decision not to participate in the 300 GeV project, do you think that many of the physicists involved tended to favour the project because they were physicists rather than for the merits of the project, and the non-physicists tended to oppose the project because they were not physicists?

33.6.10 Conclusions

You are now in possession of the salient facts you need in order to do the CMA (No. S 100 56) with this Unit, which you should now attempt. We began section 33.5 by asking about the goals of science, and the criteria by which they should be assessed. Our experiment, with this CERN 'decision-making kit' has been designed to let you participate in one such decision, and assess for yourself the complexities involved in scientific making.

But, you may ask, seeing how difficult the task is, why should we bother at all? If one is a politician, can one not just give the money to the scientists and let them fight for it amongst themselves, merely setting a top limit to what the country spends? Unit 34 attempts to answer these questions.

The point is, of course, that scientific advances, even of the sort represented by the 300 GeV machine, are not without their potential social and economic consequences. The Council for Scientific Policy report, which we quoted above, makes this point, though the consequences of the 300 GeV are hard to predict, and they are somewhat in the position of Michael Faraday, whom we left on p. 27 asking 'What is the use of a baby?'

Answers to the questions on pp. 43–4

1 (c) and (d).

2 (b).

3 (c), (f), (g).

4 That the Councils are not empowered to commit resources as long-term investments. This is sometimes referred to as 'time-span for discretion', and is a useful index of the responsibility vested in a person or group. Thus the Board of a company has a very long time-span for discretion, in order to exercise its planning decision function, whereas the man on the shop floor only makes decisions which have implications over a very short time-span.

Self-Assessment Questions

Sections 33.1 to 33.3

Question 1 (*Objectives I.3; II.1*)

An object of Units 33 and 34 is to examine some of the consequences of scientific growth since the seventeenth century. Select three of the following statements, and place them in order, to represent the main thesis which the preamble to these Units establishes.

(a) The social and historical contexts of discovery have been largely ignored in the Science Foundation Course.
(b) The use of scientific methods enables us to explain many natural phenomena.
(c) Science is an organized set of activities within society.
(d) Science depends on its instrumentation.
(e) Science and technology are intimately related in a quite specific sense.
(f) Much of the material presented has been timeless and universal.

Question 2 (*Objective II.2*)

Reference is made to some of the constraints that determine the course of science. Which one of the following represents best the context of the 'constraints' referred to?

(a) The nature of the British educational system.
(b) The directions taken by the Industrial Revolution.
(c) The nature of relevant decision-making steps and processes.
(d) The cultural heritage of the seventeenth and eighteenth centuries.
(e) The pressures of international political aspirations.

Question 3 (*Objectives I.3*; *II.1, 2*)

Write down in about thirty words why it is important to study the nature and consequences of scientific growth.

Question 4 (*Objective I.3*)

The statement that 'exponential scientific growth can continue indefinitely' is: reasonable/unreasonable?

Question 5 (*Objectives I.1, 2, 5*)

Give some examples of the ways in which the growth of science over the past one or two hundred years is reflected in changes in the organization, operation and financing of scientific endeavour during this period.

Question 6 (*Objective I.3*)

(i) Which of the following provide a precise index of scientific growth in a community? (Choose one, more than one or none.)

(a) The number of practising scientists at work as a percentage of the total working population.

(b) The percentage of the gross national product spent on 'science'.

(c) The number of scientific journals in which the work of the scientists in the community is published.

(d) The number of pages in scientific journals devoted to scientific work done in the community each year.

(ii) Specify clearly the reasons for your answer to (i).

Question 7 (*Objectives I.2, 3, 5; II.4*)

Why has a choice to be made in allocating resources to scientific research in the UK? (Choose one, more than one, or none of the following.)

(a) Because of competition for funds between the CSP and the Arts Council.

(b) There are not enough scientists to do all the research society would like to see done.

(c) There is not enough money to pay for all the research society would like to see done.

(d) There are not enough universities to do all the research society would like to see done.

(e) There are not enough decision-making bodies to consider all the research projects society would like to see done.

(f) Not all projects are equally desirable socially and therefore choices as to social merit need to be made.

Question 8 (*Objectives I.3, 5*)

What is the major problem caused by the rate of scientific growth in the UK at the present time?

Is it:

(a) the rate of growth is exponential;

(b) the rate of growth is greater than the rate of growth of the national economy;

(c) there are not enough scientists available to carry out the research projects;

(d) there are too many scientists.

Question 9 (*Objectives I.5; II.4*)

Decisions on the financing of scientific projects are made within the framework of various constraints. List the major constraints which influence such decisions.

Question 10 (*Objectives I.3, 4*)

The most useful ways of comparing the overall level of research commitment in different countries are:

(a) percentage GNP spent on R and D;

(b) amount per capita of population spent on R and D;

(c) percentage of population working in R and D;

(d) total annual expenditure on R and D.

Question 11 (*Objectives I.4; II.2*)

In the 1960s, the UK spent more per capita on R and D than any other Western European nation. However, the economic growth rate of the UK is one of the lowest in Europe—does it follow that the more spent on science, the lower the growth rate. Justify your answer.

Question 12 (*Objectives I.5; II.4*)

In the light of the Weinberg criteria and what you know about the Concorde project, how would you rate the technological, scientific and social merits of the Concorde?

Question 13 (*Objectives I.5; II.4*)

Here is a more difficult one. In recent years there has been a spectacular coverage by the world press of organ transplant surgery—in particular of heart transplant surgery. Many people have criticized these operations as being costly and ineffective and yet the work done has been successful in some areas (kidney transplants) and has stimulated useful research into the immunology of organ transplants and graft rejection as well as the more general fields of allergies etc.

How do you think the scientific, technological and social merits of the work should be rated?

Self-Assessment Answers and Comments

Question 1

We suggest: c → d → e

Examine this sequence of statements carefully and compare it with your own selection, if it is different. You may well decide your own is better, from the viewpoint you have taken.

Question 2

(c)

Question 3

We suggest:

Because the results of scientific growth are having vast and increasing effects upon the quality of human living—not all of them by any means desirable or beneficial.

But remember your answer may be equally valid. So do not reject it necessarily in favour of ours!

Question 4

Unreasonable. See pp. 13–14 if you were wrong.

Question 5

Some examples you may have thought of are:

Change from amateur science to professional science.

Change from individual working to team working.

Change from private financing to national and corporation financing.

Change from private laboratories to vast industries.

Change from 'string-and-sealing-wax' equipment to expensive, sophisticated and sometimes vast pieces of commercially produced equipment.

Question 6

(i) None—though *all* provide an *imprecise* measure.

(ii) If you chose one or more in your answer to (i) you should think again carefully. The main reason why you should have answered 'none' is that there are so many facets to the notion of 'scientific growth' that numbers of people, cost and amount published are, even taken together, a crude index only. Read again pp. 22–5.

Question 7

(c) and (f) are the most pertinent answers. The Arts Council budget is too small to be relevant and more decision-making bodies can always be created. (b) and (d) are consequences of (c). (f) is perhaps the most important reason of all, but is often expressed in terms of (c).

Question 8

(b). See pp. 12–14 if you disagree.

Question 9

We suggest:

(a) financial;

(b) scientific quality;

(c) political;

(d) technical feasibility.

Question 10

It depends what one means by useful: in general (b) and (c), but for some purposes (a) and (d) are also of value. But even answer (b) is not a very good way of comparing, for example, the USA and the UK. Why not?

The higher cost of living in the USA means that each dollar has less research spending power than it would have in the UK. This should be borne in mind when making comparisons.

Question 11

No such correlation can be made, because the 'science budget' is made up of a number of heads. For instance, in the 1960s the UK spent *more* on defence research than any other Western European nation except France. Conversely, only France and Sweden spent *less* on economically motivated research than the UK. Thus, total R and D expenditure can be a misleading guide to its potential relationship with economic growth.

Question 12

We suggest the following (but your answer may be different!). In general one must conclude that the *scientific* merit is fairly low—Concorde is not a basic piece of research into supersonic flight, it is the application of the knowledge of supersonic flight to a passenger-carrying jet. The technological merit is also slight because most of the technology of supersonic flight has already been evolved in the development of military aircraft. The social merits of the conflicting aspects of Concorde's usefulness and abusiveness to society must remain the key to the question.

Question 13

Again, the answer will be a matter of debate. But many scientists would agree that the scientific advances related to transplant techniques have some scientific merit. The technological merit may be outweighed by the development of alternative surgical devices, plastic or replacement parts for hearts, electronic pacemakers, etc. So far as the social merit is concerned, kidney though not heart transplants have clearly prolonged life. But could more lives have been saved by investing money elsewhere in hard-pressed hospital, maternity and public health services?

Ackowledgements

Grateful acknowledgement is made to the following sources for material used in this Unit:

TEXT

THE CONTROLLER, Her Majesty's Stationery Office for the *Annual Report of the Advisory Council on Scientific Policy*, *The Proposed 300 GeV Accelerator*; MACMILLAN (JOURNALS) LTD. for Professor A. R. Bishop, Professor E. H. S. Burhop, Professor Sir Brian Flowers, Professor Sir Bernard Lovell, 'British Views on the CERN Accelerator' in *Nature*, Vol. 219, July 1968; the 'SPECTATOR' for Dr. P. J. Smith, 'Toys for the Boys' in the *Spectator*, 11 July 1970.

ILLUSTRATIONS AND TABLES

THE CONTROLLER, Her Majesty's Stationery Office for Tables 1, 2 and 6; PENGUIN BOOKS LTD. for Fig. 2 in Hilary and Steven Rose, *Science and Society*.

Section 1

34.1 Social Consequences of Science

In Unit 33, you have been studying some of the processes of scientific decision-making at various levels, from laboratory bench to government. These points will be discussed further in the television and radio programmes of the present Unit 34.

If you ask yourself—why does it matter what scientific research gets done? What is the importance of scientific and technological *choice*?—then you will find only a part of the answer in the questions you have been studying in Unit 33.

It is not only the *scale* of science and technology that makes it important to understand the mechanisms of scientific and technological choice. It is the profound effects that they have on our material and social environment and even on the possible continuation of our lives. If we are to choose our science so as to enhance rather than destroy our lives, we must seek to understand more clearly both the processes and the consequences of scientific choice.

To do this, we need to go beyond the social statistics and administration of science, which occupied us in sections 1 to 4 of Unit 33, and even beyond the criteria for choice which we considered and tested in sections 5 and 6. We need to go into the substance of science itself, and try to evaluate its social consequences.

It would be an impossible, or nearly impossible, task to evaluate the social consequences of *all* the science taught so far in this Foundation Course. Indeed, there is hardly an aspect of contemporary life that has not been affected, directly or indirectly, by one or more of the basic scientific ideas you have been studying.

Several examples have been discussed explicitly, for instance: the alkali and chlorine industries (Unit 9); penicillin, pesticides and plastics (Units 10 and 13); applications of biochemistry (Unit 16); exploitation of food resources (Unit 20); applications of geophysics to detection of explosions, prospecting and earthquake prediction (Unit 22); effects on navigation and exploration of the discovery of the geomagnetic field and the compass (Unit 23); the Earth's resources (Unit 23, radio); nuclear fission and fusion (Unit 31 and the sections of Unit 34 to follow); the effects on advanced technology of the special techniques and devices needed for elementary particle physics research (Units 32 and 33).

But there are many more implicit connections. What would you say are the major industries of contemporary industrial society? Almost certainly, they include the chemical, electrical and mechanical engineering, electronics and communications (including computers, control and automation), and the nuclear energy industries.

At the risk of a certain oversimplification, you could say that the chemical industry could not exist in its present form, or on anything like its present

scale, but for the firm foundations of the Periodic Table,* the basic ideas of structure and bonding, and the theory of chemical reactions and equilibria.

These are precisely the topics you have encountered in Units 6–12 of this Course.

The apparently abstract ideas of classical mechanics (Units 3 and 4) and electromagnetism (Units 4, 23 and 28) could be regarded as the basis for most of the electrical and mechanical engineering industries. As for electronics, communications, computers and automation, these industries depend first and foremost on classical electromagnetism on the one hand, and solid state physics on the other. You have only touched upon solid state physics in this course (in Unit 5); the really important aspect of it in the present connexion is the quantum theory of the solid state, for it is this which underpins our understanding of the electrical properties of solids, and hence our ability to manufacture transistors and other electronic devices. Although there was very little room in the Course for this particular application of quantum theory, you *have* met some of the basic ideas in Units 6, 7, 29 and 30, and it was discussed in more detail in the radio programme of Unit 30.

And the nuclear energy industry depends, in its fundamental aspects, on nuclear physics (Unit 31) and, ultimately, on the equivalence of mass and energy ($E = mc^2$, Unit 4). On the technological side it depends very much on basic chemistry and metallurgy, and these in turn go back to atomic physics, classical mechanics and solid state physics.

For a long time, it has been taken for granted that the consequences of scientific advance and technological innovation are beneficial, or at least neutral, if they are without particular social consequences. However, in recent years many people have tended to look more questioningly at scientific developments, and indeed have voiced the opposite belief; that such advances carry in their turn inevitable *harmful* consequences as well. They cite war technology, pollution, overpopulation, invasion of privacy by computers, etc., as examples of such undesirable effects. And there have indeed been claims that the negative effects of science outweigh the positive ones. These views have achieved widespread currency. They are voiced, in the television programme of this Unit, by a young 'drop-out' research student, Peter Harper, and the views of some of those who have written most seriously on this topic are discussed in *Science and Society*, pp. 253–61, which you should read if you have time.

Obviously we do not share this rejection of science—or we would not have constructed this Course. And presumably you do not, or you would not have come this far with us. But we think it important that we all—you as a student, and we as teachers, of science—should understand both the nature of the challenge that these views represent, and something of the real complexities of the social interactions of science and society. This is the function of the two case studies which follow. But before embarking on them, pause to think about the general types of social effects of science and technology that can be identified.

We can distinguish between three categories, among others:**

(a) A desirable innovation has unforeseen side-effects which are undesirable.

* *And, as you saw in Units 6–8, the Periodic Table is to be understood in terms of the quantum theory of atomic structure.*

** *There are, of course, innovations without side-effects, and innovations with unforeseen, but desirable, side-effects*

(b) A desirable innovation has undesirable side-effects which *are* foreseen, but generally regarded as acceptable.

(c) An innovation is applied deliberately for a particular purpose, irrespective of whether its effects are generally desirable. (In such cases there is usually the appearance, at least, of advantage to some sectional interest. Most innovations in weaponry are in this category.)

We can consider briefly examples of each of these.

(a) The side effects, or unexpected consequences, of new techniques are often either difficult to predict or come to light only after their introduction. Many of you will have become familiar with one very conspicuous example of the undesirable consequences of what may otherwise be beneficial technological advances, that of pollution, which has been much discussed in recent years. Pollution generally relates to the accumulation in the environment of actual or potentially harmful substances, either introduced deliberately for one particular purpose, but now known to have other effects, or produced as a by-product of another process. Or it may relate to a changed physical or biological state caused by human intervention: the heating of rivers by industrial processes (thermal pollution) and their organic pollution by sewage effluents, are examples.

pollution

An example of a deliberate introduction of a substance originally believed to be purely beneficial is that of DDT, an insecticide developed during the Second World War and found to be very effective in the control of insects, particularly the body louse and malaria-carrying mosquito, and almost non-toxic to humans. DDT was used extensively after the war for the control of malaria (and indeed still is). More recently, however, it has been shown that, because of its extreme stability, DDT, once released into the environment, accumulates there. Its metabolic products are lipid soluble and are now present in the fatty tissues of almost every living organism which has been studied, including antarctic penguins and, of course, human beings. So high has become the concentration of DDT in humans in the United States for example, that in some areas human milk contains quantities which, if present in animal carcasses, would be regarded as making them unfit for human consumption. Whilst DDT is not, even at these concentrations, directly poisonous to humans, its use has had complex ecological effects (Unit 20) and may result in the extermination of certain predator birds and fishes which are high in food chains and which therefore accumulate substantial quantities of DDT. As a consequence of the accumulation of DDT, some such species seem recently to be showing a catastrophic drop in fertility, whilst some of the pest insects have developed immunity (Units 19 and 20). (Some of these cases are cited in the recommended background material for these Units, Rachel Carson's *Silent Spring*, and Kenneth Mellanby's *Pesticides and Pollution*.) It is, of course, unwise to jump to the conclusion that the use of DDT has done more harm than good. Most people will prefer not to suffer malaria, or have their children die from it, rather than worry unduly about the fate of certain bird species. Perhaps more to the point is the extent to which immunity has spread in the mosquito population, making it necessary to look for alternatives to DDT irrespective of the pollution issues.

The point is simply an example of one unexpected effect of the introduction of a new technology.

(b) An undesirable, but scarcely unexpected effect of technology is that of the pollution of the atmosphere by the products of industrial processes. Since the beginning of this century, the carbon dioxide concentration of the Earth's atmosphere has increased by some 10 per cent as a result of such processes—enough possibly to put in train a variety of ecological

effects which one cannot yet predict with certainty.* And you will recall a specific effect of industrial pollution of this sort from the TV programme of Unit 19, where you saw the increased distribution of the melanic form of a moth in Britain following the growth of heavy industry and hence soot-blackened trees.

The Home Experiment which goes with this Unit (and which you will already have begun) provides you with a further example of this type of pollution and involves you in what is perhaps a unique attempt to measure and quantify it, by determinating in your own neighbourhood the level of sulphur dioxide in the atmosphere. You will already have read the rationale of this experiment before entering upon the measurements, and we remind you that the results will be discussed in the final television programme of the Course in which we shall invite experts on air pollution to comment on the distributions you have obtained.

(c) But the examples we wish to provide as case studies in this Unit are of the *deliberate* application of science and technology in the solution of particular problems and of the consequent social and political implications. We have chosen two for examination, each of which will be treated briefly in the main text. One of them, nuclear energy, will be considered at greater length in this Unit's radio programme. You have already met the basic science relevant to each during the Course.

The first example traces the development of techniques for the 'fixation' of atmospheric nitrogen as nitrate and the consequences of the large-scale use of nitrates in industry and agriculture.

The second example is that of nuclear energy. Its large-scale applications, both peaceful and military, have created quite unprecedented problems connected with the biological effects of ionizing radiations.

* *See the Home Experiment Notes for Units* 33 *and* 34.

34.2 Large-scale Technological Applications of Basic Science—Two Case Studies

In considering the two case studies that follow, keep in mind that, though both are examples of the deliberate application of science and technology on a very large scale for military and economic purposes, in neither case would such an application have been possible except on the basis of certain fundamental scientific knowledge.

The technological practicability of nitrogen fixation depends on an understanding of chemical reaction kinetics, in particular Le Chatelier's principle (Unit 9).

As for the liberation of energy from nuclear fission—whether explosively in a bomb, or in a controlled fashion in a nuclear reactor—you have already seen (Unit 31) that nuclear technology depends upon an understanding of basic nuclear physics.

Indeed, we can trace the scientific basis of nuclear energy right back to Einstein's questioning of the meaning of simultaneity and his consequent postulation of the relativity principle and the invariance of the velocity of light—for it was from these premises that he deduced his now famous equation $E = mc^2$ (Unit 3).

You may have noticed that in the last paragraph of Unit 33 we spoke of 'scientific advances, *even* of the sort represented by the 300 GeV accelerator'.

We should, perhaps, question the assumption, implicit in using the word '*even*', that research in elementary particle physics (for which large particle accelerators are required) is most unlikely to lead to any practical applications.

Could Einstein have foreseen that his equation would have such profound significance as to require explanation in mass-circulation newspapers? Did Rutherford, even, foresee such consequences?

You may recall his categoric assertion (quoted in Chapter 1 of *Science and Society*) that 'anyone who looks for a source of power in the transformation of atoms is talking moonshine'.

The fact is that basic science generally gets applied, sooner or later, and that such application can and does drastically affect our lives.

Consider what Victor F. Weisskopf, then Director-General of CERN, wrote in his Introduction to the CERN Annual Report for 1963:

> Our knowledge of the inner structure of the nucleon increases fast and we are beginning to discern the first indications of order and regularity in this world. . . . The perspectives of research which are opened up by the new neutrino physics are bound to lead to a deeper understanding of many questions regarding the nature of elementary particles.
>
> The latest discoveries in radio-astronomy lend special significance to these questions. The astronomers have found certain galactic systems in which energy is produced at a rate that is larger than anything we have observed in ordinary galaxies by a factor of at least one million. Possibly, the newly observed phenomena might be examples of processes of the kind we are studying in high-energy physics. Atomic physics led to an understanding and control of energy production by ordinary combustion, nuclear physics gave the explanation of energy production in the sun and in the stars by nuclear phenomena, which we try to control in fission and fusion processes.

None of these processes would be energetic enough to account for the new observations. We are probably facing here a new form of natural phenomenon which can only be understood by research of the type which is done with large accelerators. The new discoveries are an illustration of the fundamental importance of this research for science as a whole.

Perhaps we should drop the word '*even*', even when we speak of fundamental research that seems totally remote from application.

As you read the stories of nitrogen fixation and of nuclear energy, bear in mind the one-time remoteness of *their* scientific beginnings.

34.2.1 Nitrogen fixation

The title of this case study is a deceptive one. It sounds dry and uninteresting. Yet it has to do with one of the most fascinating developments of nineteenth-century chemistry, developments that changed the course of history in this country, that have shaped much of our present world, and that touch upon some of the major political and economic problems of our time.

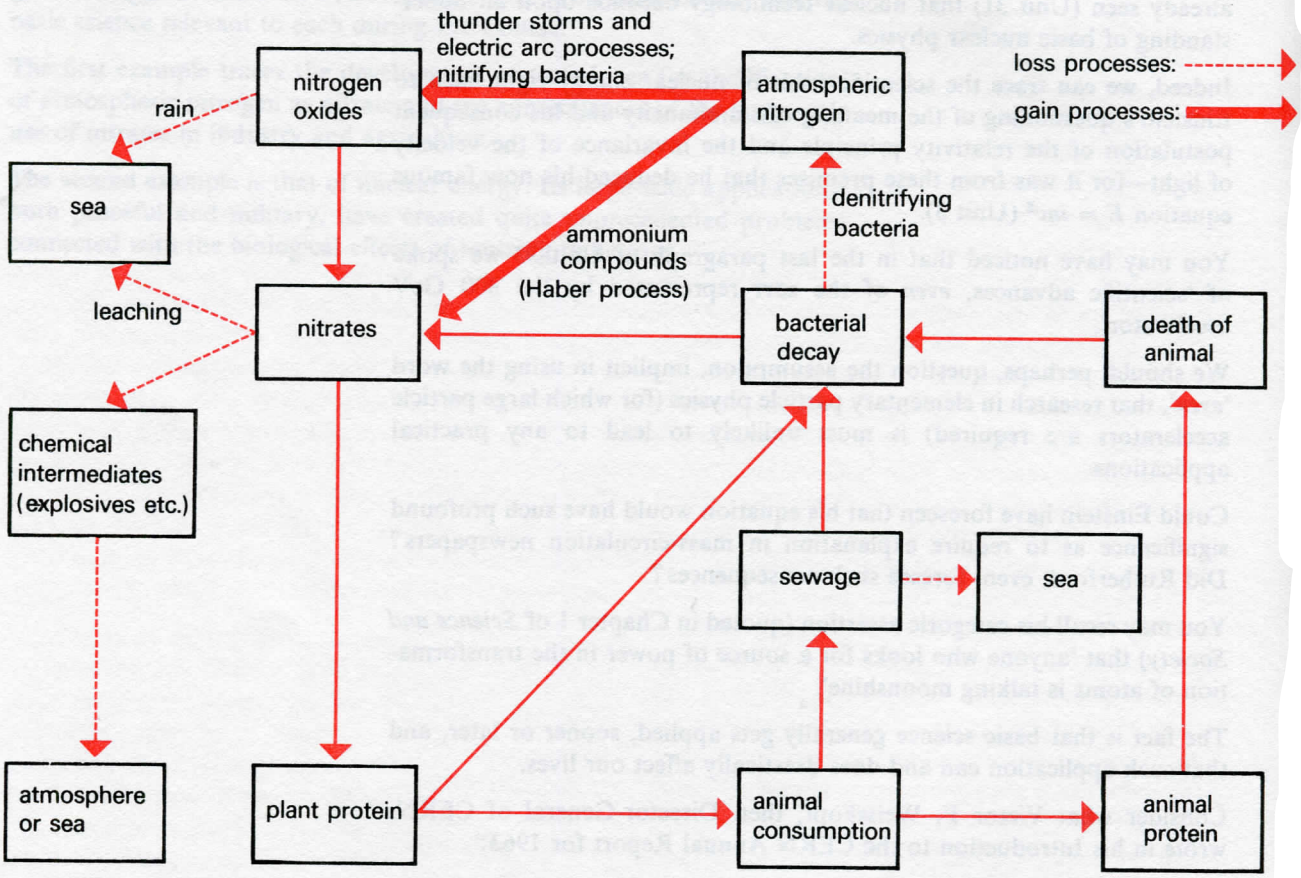


Figure 1 A simplified nitrogen cycle.

The nitrogen cycle

From previous Units (10, 13, 14–17, 18 and 20) you will have seen how nitrogen-containing compounds such as proteins and nucleic acids are essential components of all living organisms. These nitrogenous compounds are virtually all derived from plants which in turn derive them from nitrates in the soil. These nitrates in their turn are formed by bacterial oxidation of ammonium compounds produced by the bacterial decay of plant or animal proteins from dead organisms. So for almost any ecological system we can envisage a cycle such as that shown in Figure 1, which is a simplified version of Figure 3 in Unit 20.

In such a simple system, the amount of 'fixed nitrogen' remains more or less constant. Minor variations occur because some bacteria cause complete degradation of the nitrogenous compounds to nitrogen itself; this loss is usually made up by still other bacteria which can convert atmospheric nitrogen into compounds and which are therefore called *nitrogen-fixing* bacteria. Some small contribution to nitrogen fixation is also made by lightning flashes, which cause combination of some of the nitrogen and oxygen in the air in the immediate proximity of the flash. The oxides of nitrogen so formed (and those emitted by internal combustion motors) are washed from the air by rain and are converted to nitric acid and nitrates (Fig. 1).

The important point to realize is that nitrogen is an unreactive gas and that, surprising though it may seem, a green plant surrounded by air which contains 80 per cent of nitrogen will nevertheless die—in effect of nitrogen-starvation—if it is not able to absorb chemically-combined nitrogen from the soil, dissolved in the water absorbed through its roots.

Fertilizers

Nitrogenous materials, especially urine and dung, were used for centuries as fertilizers in agriculture before the reason for their beneficial effects were known.

In the early part of the nineteenth century, the dependence of growing plants on chemically-combined nitrogen was demonstrated by a number of distinguished scientists, including de Saussure, Boussingault, and Justus von Liebig. De Saussure is known for his discovery that carbon dioxide absorption accounts for nearly all the increase in dry weight when plants grow, and Liebig for his condenser and for his early studies of physiological and agricultural chemistry. Among chemists, Liebig is also distinguished by his importance as a great teacher.

The increased knowledge resulting from the work of Liebig and his contemporaries led to a demand, wherever agriculture was practised intensively, for nitrogen compounds to supplement the natural supply of the soil. It was found that nitrogenous fertilizers such as potassium nitrate ('saltpetre'—from India), or guano (the accumulated droppings of seabirds from islands off Peru) could double or even treble the yield of grain crops. The importance of this—at a time when, with the beginnings of industrialization and the advances in medicine, the population of Europe was growing rapidly—is obvious.

saltpetre

Two new sources of fixed nitrogen were developed in response to this demand. One was the large deposits of sodium nitrate found in Chile—Chile saltpetre or 'caliche'. Export of this material to Europe started in the middle of the nineteenth century. The second source was the new coal-gas industry. When coal is heated in the absence of air it breaks down to give: a gas (coal-gas); two liquids, one coal-tar and the other mainly water containing dissolved ammonia (ammoniacal liquor); and a solid residue, coke. With the development of coal-gas lighting in the nineteenth century and the demand for coke in the iron and steel industry, ammoniacal liquor became available on a large scale and could be processed to yield nitrogenous fertilizers such as ammonium sulphate.

Chile saltpetre

Explosives

Agriculture was not the only industry whose demands for fixed nitrogen developed dramatically in the first half of the nineteenth century.

From 1242 to the 1860s, virtually the only explosive available was gunpowder (a mixture of potassium nitrate, sulphur and charcoal). However,

in 1846 the Italian chemist Sobrero first made the high explosive nitroglycerine and so became one of the founders of a new major industry. Nitroglycerine explodes with great violence and, although used for blasting, has to be handled with great care because of its sensitivity to shock. When nitroglycerine is absorbed onto an absorbent material known as kieselguhr it forms the high explosive known as dynamite, which is much less sensitive and is easy to handle.

nitroglycerine

dynamite

It was the development of this process which made the fortune of the Swede Alfred Nobel, and hence enabled him to endow the Nobel Prizes for science—and peace. He came to believe that with such explosives, weapons would be so terrible as to lead to the end of war! Other high explosives such as gun-cotton were also developed at this time and were used in great quantities in railway construction and mining, which were the concomitant of the growth of industrial Britain.

Dyestuffs

Similarly, until the middle of the nineteenth century, virtually the only dyestuffs available were those derived from plants, such as indigo and madder. But in 1856, the English chemist W. H. Perkin made the first synthetic dyestuff, mauveine, a nitrogenous coal-tar derivative, and in doing so laid the foundation for the dyestuffs industry. In comparison with the natural dyestuffs, the synthetic dyestuffs were cheap, were much less susceptible to fading, were available in a greater range of colours, and were much better standardized. As a result, the natural dyestuffs were eliminated from the market. The social consequences of this change from natural to synthetic dyestuffs were far-reaching: the immediate consequence was that the producers of natural dyestuffs very soon lost their markets, but another rather more subtle effect was that colourful clothes gradually became available to all and were no longer confined to the well-to-do.

mauveine

The discovery of synthetic dyes led to the growth of a vast chemical industry dominated, not by England, where the initial basic discovery of mauveine had been made, but by *Germany*. This was a striking example of the importance of a sound industrial base for the exploitation of laboratory discoveries. This point is discussed further in *Science and Society* (pp. 28–36) and in *The Roots of Present-Day Science*.

All these demands for fixed nitrogen in the latter half of the nineteenth century were too much to be satisfied by Chile saltpetre and ammoniacal liquor. In his Presidential Address to the British Association in 1898, Sir William Crookes forecast that, because of the limitations on the supply of fixed nitrogen and the steadily increasing demands of the rapidly growing population, the wheat lands would by 1931 become inadequate to meet the world's requirements for bread. Moreover, in the tense political situation which developed in Europe at the turn of the century, it was obvious that a nation cut off from the supply of Chile saltpetre would be unable to maintain an adequate supply of munitions.

The obvious source of this fixed nitrogen was the nitrogen of the air—a virtually unlimited supply and free for the taking. Crookes suggested that the problem of fixing atmospheric nitrogen was one of major importance and would 'lead to the development of a mighty industry destined to solve a great food problem'. However, the problem was more easily recognized than solved, for one of the main characteristics of elementary gaseous nitrogen is its comparative unreactivity. It is not as unreactive as the noble gases, indeed many thousands of nitrogen compounds are known; nevertheless under ordinary laboratory conditions it reacts with very few reagents. The problem then was, by some process capable of being used cheaply on a vast scale, to induce the unreactive nitrogen to form a compound which could be a source of fixed nitrogen suitable for both agricultural and industrial purposes.

The Haber-Bosch process

In spite of these difficulties, several successful processes were developed during the period 1904–1908. Scarcely surprisingly, in view of what has already been said, the most successful of these, the Haber-Bosch process, was developed in Germany. In this process (which was discussed in Radio Unit 12), nitrogen and hydrogen react at high pressures in the presence of a catalyst at a temperature of about 450° C to form ammonia; the ammonia can in turn be converted to nitric acid. The process has several points of scientific interest and is discussed in more detail in Appendix 1.

A pilot plant working by Haber's process was first operated in 1910 and the full plant, with a capacity of 30 000 tons of ammonium sulphate per annum, began production in 1913. As with many scientific and technological developments, war was to prove the spur to its massive exploitation. Britain and her allies had control of the sea-routes by which Chile saltpetre and Peruvian guano were shipped. Germany and the Central Powers were cut off from this source of fixed nitrogen, for agriculture or explosives, and were forced to innovate or perish.

With the advent of the First World War in 1914, the capacity of the first plant was expanded to 120 000 tons of synthetic ammonia per year and at least one other major plant was constructed. There can be little doubt that Haber's process was of primary importance in the First World War. It provided the Central Powers with the fixed nitrogen they needed for munitions and for food production. The other possible processes, none of which has been adopted on so wide a scale as the Haber process, demanded the availability of cheap electricity in vast quantities.

But even this provision was not adequate, as Fritz Haber's son, L. F. Haber has written in his book *The Nitrogen Problem*:*

> One of the chief reasons why Germany lost the war was not through shortage of explosives but because the army took such a large share of the nitrogen compounds that there was not enough left for the farmers. In 1917 and 1918 the harvests were disastrously bad. Ironically, in the country where the solution to the nitrogen problem had been found, the wheat failed and people went hungry.

Fritz Haber became, for a time, one of the most important figures in German science. He assisted the German war effort in other ways, too. He was responsible for the fact that Germany was the first nation to use chemical weapons on a large scale, developing the production of chlorine as a poison gas and visiting the front to supervise its use and improve the munitions in which it was dispensed. But, ironically, Haber, whose service to the German cause was indisputable, was Jewish. With the coming of the Nazis in the 1930s, he was driven from his University post (like Hans Krebs, who described this episode in the radio programme of Unit 15) and took refuge in England. He died, a broken and disappointed man, not long after.

Some social consequences

What, then, were the consequences of Haber's success in developing his synthetic ammonia process?

One consequence was that it prolonged the First World War by a year or two (according to some estimates) in which period nearly a million people died who might otherwise have lived.

But the vast expansion, since the First World War, of production of fixed nitrogen for fertilizers must be counted on the credit side of the balance. It has been estimated that world production of fixed nitrogen for fertilizer

* *Longmans, Penguin Books*, 1966.

in 1970 was 35 million tons*—double the production in 1964–5. The projected demand 1975–6 has been estimated at 57 million tons—a staggering figure even when set against the total amount of nitrogen circulating in the various natural cycles per year, which is about 10^9 or 10^{10} tons. Here, surely, must be an example of how, through large-scale application, science can, as Crookes foresaw, solve one of the greatest human problems —that of malnutrition.

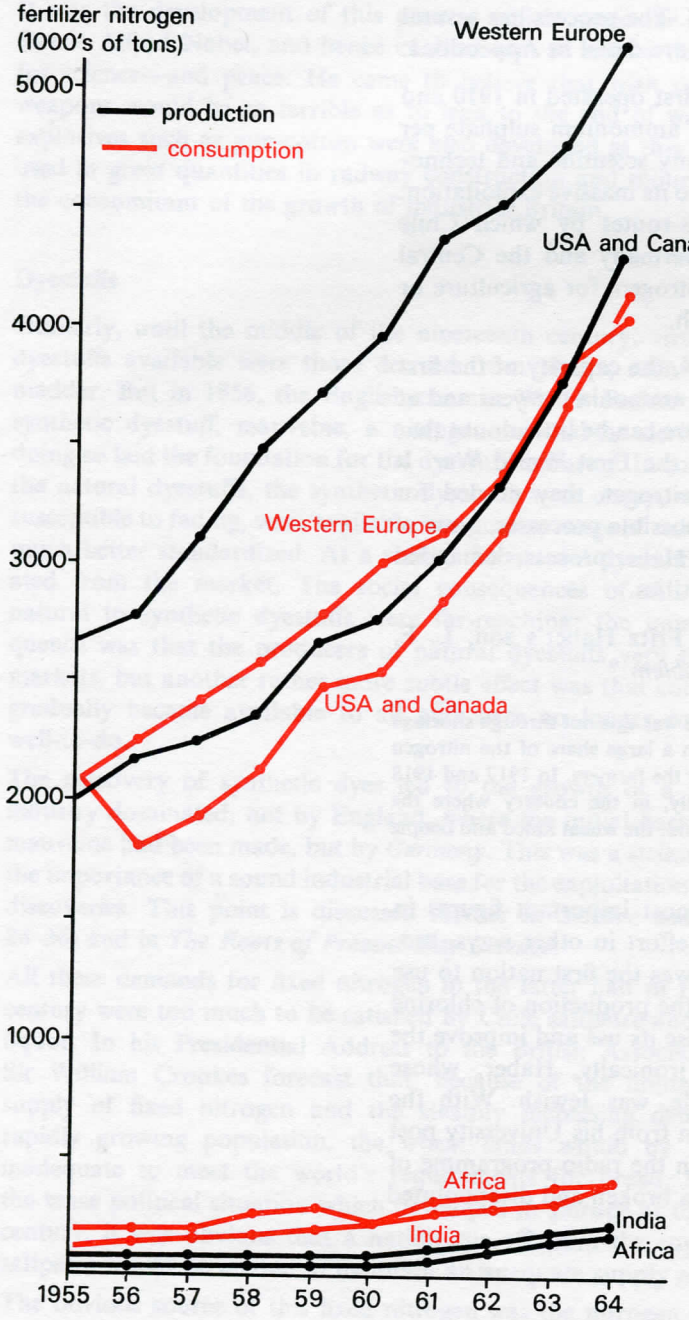


Figure 2 Production and consumption of fertilizer nitrogen, 1955–1964.

However, it must be remembered that malnutrition involves such matters as the *distribution* of food as well as its production; hunger is an aspect of underdevelopment, and inadequate use of fertilizer is only one of many characteristics of an underdeveloped agriculture.

Might it not be logical, nevertheless, to expect some correlation between global *need* and global *use* of fertilizers?

Figure 2 shows that the use of nitrogenous fertilizers has, in recent years' been consistently and considerably greater in the developed countries than in the underdeveloped ones.

* *As nitrogen; equivalent to about* 150 *million tons of fertilizer.*

It is clear that the potential benefits of science are not necessarily applied where they are most needed. The application of science depends quite evidently on the social and political circumstances.

Yet there is little doubt that nitrogen fixation has had a major effect on the lives of a lot of people, particularly in the industrially developed parts of the world. Quite apart from fertilizers, there are many examples of synthetic materials which contain combined nitrogen and which are important to everyday life—synthetic fibres such as nylon, almost all dyestuffs, the majority of medicinal drugs, urea-formaldehyde and melanine plastics, all (non-nuclear) explosives. (Yet even these uses are not necessarily wholly advantageous.)

You will have noticed, in Figure 2, the large quantities of nitrates that have been used as fertilizer in the United States. It is here that our case history takes an unexpected and significant turn, and we come upon a new problem. It has to do with water supplies. One way in which nitrogen is lost to the nitrogen cycle is by nitrogenous compounds finding their way to rivers and to the sea. This can happen through sewage disposal and through leaching from the soils, especially of the easily soluble nitrogenous fertilizers. What is important here is not so much the loss, as the possible effects of these nitrogenous compounds on water supplies into which they run off. The growth of green plants in water is encouraged by nitrogenous fertilizer in the same way as it is encouraged on land. The term *eutrophication* is applied to such processes of enrichment of water with nutrients, especially those which can directly fertilize the growth of aquatic plants and algae. The term is derived from the adjective 'eutrophic', which was first applied to lakes that are rich in plant nutrients in contrast to nutrient-poor 'oligotrophic' lakes. Adding nutrients to oligotrophic waters stimulates plant growth and may increase fish production, but enrichment of any water may also have adverse effects.

eutrophication

These adverse effects can be of three kinds; the development of blooms of suspended algae; the excessive growth of weeds; and the direct toxicity of nitrate and nitrate ions to young bottle-fed babies. This third problem is becoming acute in some places. There are indeed areas of the USA where normal drinking water cannot be used for babies, because of its nitrate toxicity, and where mothers are obliged to buy specially bottled water. As the demand for water increases, it becomes more and more necessary to use and re-use it. Thus, these adverse effects of eutrophication are causing more concern.

Of these effects, algal blooms are probably the most dramatic. The algae multiply to such an extent that sunlight can penetrate only a few inches into the water. If there is no mixing, the deeper-lying algae die off and decay. The oxygen dissolved in the water is all used up and fish and other animals die. Eventually, under extreme conditions, the lake 'dies'—the most spectacular example of this is Lake Erie in the USA, enriched by untreated sewage discharged from the great cities on its shores. But the same problems are apparent in many British rivers.

algal bloom

Algal blooms occur in some natural waters and also in reservoirs, where they can be a nuisance to the waterworks engineer because they clog the filters and some produce odours and colours in the water as they decay. The problem may be acute where there is no alternative source of supply, but the Metropolitan Water Board (and others) cope every year with blooms by resting affected reservoirs and using others. Blooms are most likely in lowland areas where reservoirs are filled from rivers which are rich in nutrients.

Enrichment of the rivers may cause excessive growth of rooted plants and of algae that can attach themselves to stones. Some of these growths may interfere with land drainage or with navigation; others affect the survival of fish and other animals and present an amenity problem. It should be

emphasized, however, that the relationship between enrichment phenomena such as algal blooms and the use of fertilizers needs further investigation.

Actually, nitrogenous fertilizers are not the only cause of eutrophication. Another source of fixed nitrogen may be the various nitrogenous compounds present in motor car exhaust emissions. (See Table 1 in the Home Experiment Notes for these Units.) Other sources are urban sewage, industrial effluent and animal waste. The relative importance of the various sources of fixed nitrogen will vary from one river to another and with the time of the year.

It has been estimated that in Britain, on the average, the contribution from nitrogenous fertilizer is about 10 per cent. In the USA, on the other hand, the average has been estimated at 50 per cent. These figures reflect the difference in population density and in the agricultural usage of the land.

Another essential nutrient involved in eutrophication is phosphate—another fertilizer, but also present in sewage, largely because of its presence in domestic non-soap detergents, which are also coming to be regarded as a technological development generating unexpected and undesirable side-effects.

The exact causes of eutrophication may vary from one case to another, as the contribution of the various possible causes differs from place to place. It does, however, illustrate another aspect of the nitrogen cycle, one related not to our category of deliberate effects of technology like explosives and fertilizers, but to 'accidental', or unforeseen, consequences.

It almost appears as if we cannot do without fertilizer, but we may not be able to do with it on the present scale of its application in Western Europe and North America for much longer. One of the most influential of the prophets of 'doom through pollution', Barry Commoner, in the USA, who has done much to illuminate the effects of nitrogenous fertilizers, has likened the problem to that of a 'drug addict, needing his heroin even though its use is likely to result in death'. This analogy may well be overlurid, but the problem remains.

Summary

The rapid increase in the world's population from the early nineteenth century led to a corresponding increase in the demand for foodstuffs—all derived directly or indirectly from plants—and so in the demand for nitrogenous fertilizers. The rise of the chemical industry, especially the explosives and dyestuffs industries, in the latter half of the nineteenth century also led to a demand for sources of combined nitrogen. For a time these demands were satisfied by supplies of sodium nitrate from Chile and ammoniacal liquor from coal, but in the early part of this century successful processes—especially the Haber process—for 'fixing' atmospheric nitrogen were devised with the result that there is no longer any technical difficulty in supplying all the world's needs for combined nitrogen. An over-abundance of nitrogen can lead to problems of eutrophication of water supplies. However, a successful nitrogen-fixation process is essential to maintain the present world population under present conditions, provided that the fertilizer produced can be distributed to where it is most needed to advance agricultural productivity.

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The intensive effort that went into the development of a nitrogen fixation process was evidently due to a combination of economic and military-strategic pressures.

The even more intensive effort that went into releasing energy from nuclear fission was due *entirely* to military-strategic pressures. The 2 000 million dollars spent in four years on the Manhattan Project had the clear-cut objective of producing an atomic bomb. A case can, however, be made for the view that the actual *use* of the atomic bomb against Hiroshima on 6 August 1945 and against Nagasaki three days later was a matter of national and international politics rather than one of military strategy.*

Some of the moral problems for the 'atomic scientists' who persuaded one United States President to launch the project to make an atomic bomb, but who failed to persuade his successor not to use it, were discussed in the radio programme of Unit 31.

The first quarter-century of what has been termed 'the atomic age' has seen a considerable expansion of the nuclear energy industry, particularly the generation of electrical energy from nuclear reactors. It is important to realize, however, that much of the social pressure behind the development of nuclear energy over this period (1945–70) has been military and political, rather than economic in character. As you learned in Unit 31, a nuclear reactor can be used to 'breed' fissile plutonium (^{239}Pu) from ordinary uranium (^{238}U).** The material needed to make a bomb is ^{239}Pu, but to produce this in a conventional reactor requires a special and highly uneconomic fuel cycle. In a strangely ambivalent way, the military requirement for weapons-grade plutonium has at one and the same time provided the social pressure for the development of nuclear reactor installations generating electrical power, and at the same time restricted their fully economic exploitation. This applied particularly to the period up to about 1960–2, when the stockpiles of nuclear weapons were being built up. The emphasis has shifted now to the design of nuclear energy installations of high efficiency and of fuel cycles optimized to breed fissile fuel for energy production rather than for weapons.

nuclear weapons

Any attempt to evaluate the social consequences, actual or potential, of nuclear energy must include both its military and its peaceful uses.

In the former category, there is the actual use of the two nuclear weapons in 1945, the testing of nuclear weapons that has gone on practically continuously since then, and the potential consequences of the use of existing stockpiles of nuclear weapons in a future war.

nuclear test explosions

The direct consequences, for the people of Hiroshima and Nagasaki, and the indirect consequences for the people of a number of other countries of the atomic arms race that followed, have been analysed and discussed in a great many publications, and we shall not concern ourselves with these in this Course.

In the period from 1945 to 1958, the year when negotiations started which led eventually to the signature of the 'Partial Test-Ban Treaty' in Moscow

* *For instance, Professor P. M. S. Blackett, F.R.S., in his book* The Military and Political Consequences of Atomic Energy, *Turnstile Press*, 1948, *concluded that 'the dropping of the atomic bombs was not so much the last military act of the Second World War, as the first act of the cold diplomatic war with Russia now in progress'.*

But there is little doubt that other factors entered into the decision to use the bomb—such as the 'internal momentum' of the project itself, military pressure to test both types of weapon (plutonium and uranium) under field conditions, and various external political pressures on the protagonists. Opinions differ on the relative importance of these factors.

** *An alternative process for 'breeding' fissile material is that of transforming* ^{232}Th *into* ^{233}U.

in October 1963, there were over 250 nuclear test explosions, nearly all of them in the atmosphere.

During the period 1959 to October 1963, there were about 200 more test explosions, of which about 75 were underground.

Between the signature of the Partial Test-Ban Treaty in October 1963 and July 1970, there were a further 318 nuclear test explosions, of which all were underground except the 20 French and 10 Chinese tests.

These figures are summarized in Table 1 and in Figure 3.

It is significant that, though the annual rate of testing *above* ground has gone down from about 32 before the Treaty to about 4.5 since, the annual rate of underground testing has gone up from about 7 before the Treaty to about 43 since, and the rate for all testing has in fact increased from 39 explosions a year in the 12 years before the Treaty to 47 explosions a year in the 7 years after it. Thus the Partial Test-Ban Treaty cannot be said to have had much effect on the nuclear arms race.

As you know, a nuclear explosion releases a vast amount of radioactive debris—particularly if it takes place on or near the ground, or under water—and this radioactive material, sooner or later, comes down as 'fall-out'. Apart from accidental 'venting', which has occurred on a number of occasions, leading to the escape of radioactive material into the atmosphere, underground tests do not contribute to fall-out.

fall-out

Table 1

Reported nuclear test explosions in the period 1945–July 1970*

Period	USA	USSR	UK	France	China	All
1945–1958	172	59	21	—	—	252
1959–1960	—	—	—	3	—	3
1961–1962	98	74	2	3	—	177
1963 (to 10 October)[c]	17	—	—	1	—	18
Undated additions	23[a]	30[b]	—	—	—	53
TOTAL to 10 October 1963[c]	310	163	23	7	—	503
10 October 1963—3 July 1970[d]	221	64	2	21	10	318
TOTAL 1945–1970	531	227	25	28	10	821

One of the consequences of nuclear weapons testing has therefore to be understood in terms of the effects on man of such 'fall-out'. The biological effects of radioactive fall-out are discussed in Appendix 2. The public pressure which found expression in the United Nations' Conference on the Discontinuance of Nuclear Weapons Tests (the 'test-ban conference') in 1958 was undoubtedly due, in part, to concern at the increasing levels of radioactive fall-out. The Conference led, eventually, to the signature in October 1963 of the partial 'test-ban treaty', prohibiting nuclear explosions

partial 'test-ban treaty'

* *Taken from the* SIPRI Yearbook of World Armaments and Disarmament, 1969–70 (*Duckworth*, 1970).

[a] *Tests reported as having taken place between* 15 *September* 1961 *and* 20 *August* 1963.

[b] *Tests reported as having taken place on unspecified dates before* 1959.

[c] *The Partial Test-Ban Treaty was signed on* 10 *October* 1963.

[d] *Tests conducted from* 1 *January to* 3 *July* 1970, *scaled up to an equivalent number for a full year.*

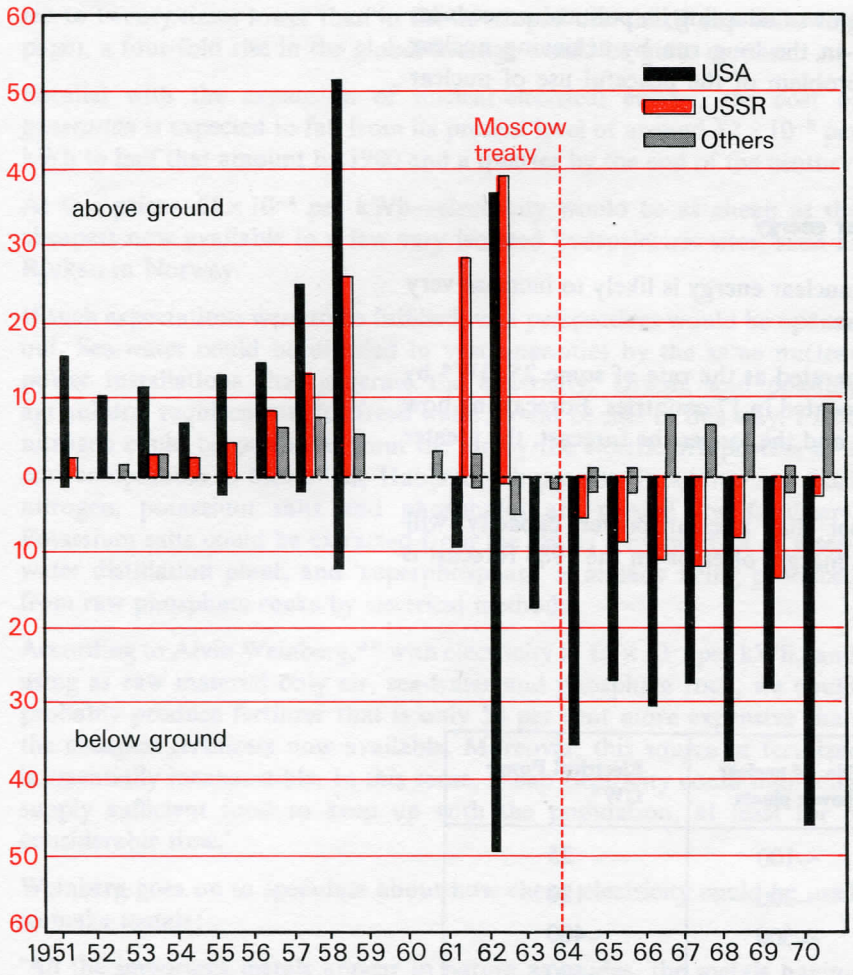


Figure 3 *Nuclear weapons tests, 1951 to July 1970.*

in the atmosphere, in outer space and under water, but not underground. The problem of extending the treaty to include underground test explosions was the subject of discussion in the radio programme of Unit 22.

The use of large numbers of nuclear weapons in war, as would inevitably happen in the event of a conflict between the nuclear powers, would not only kill several hundred million people immediately, through the direct effects of blast, fire and radiation, but also produce such vast quantities of delayed fall-out as to threaten even the survival of the human species.

nuclear war

A short paper presented by Professor B. T. Feld to the Twentieth Pugwash Conference on Science and World Affairs (Fontana, USA, September 1970)—*On the consequences of nuclear war—a reminder*—is reproduced in full in Appendix 3.

We are not concerned here with making the only too obvious point that the social consequences of the military applications of nuclear energy are manifestly evil.* The important thing about *this* aspect of the use of nuclear energy is that it is the *first* example in human history in which a technological development threatens humanity with self-extinction. It may not be the last example.

* *We are referring, of course, to the* use *of nuclear weapons in war. There are some people who believe that the existence of nuclear weapons has in some way contributed to the preservation of 'peace through mutual deterrence'. It is generally accepted, however, that this can at best be regarded only as a temporary and precarious balance, and that the United Nations' aim of nuclear (and, indeed, general) disarmament can be the only safeguard in the long run.*

Assuming that humanity is capable of so adapting its political procedures as to avert this particular threat—in the long run by achieving nuclear disarmament—there remains the problem of the peaceful use of nuclear energy.

Perspectives and problems of nuclear energy

The generation of electricity from nuclear energy is likely to increase very rapidly in the next twenty-five years.

At present, electrical energy is generated at the rate of some 25 GW* by about 110 nuclear power stations located in 17 countries. Forecasting how this figure will increase is difficult, and the longer the forecast, the greater the margin of error.

For example, it has been forecast that nuclear power capacity will increase as shown in Table 2. The margin of error on the 1985 forecast is at least +30 per cent.

Table 2

Year	No. of countries	No. of nuclear power plants	Electrical Power GW*
1971	17	~100	25
1975	22	~300	130
1980	>30	~500	~400
1985	?	?	>600
2000	?	?	>4 000?

You may appreciate the significance of such an expansion of electrical power from *nuclear* sources if you compare it with the corresponding forecasts for electrical power from *all* sources. This is expected to double every ten years for some time to come, increasing from about 1 000 GW in 1970 to 2 000 GW in 1980, 4 000 GW in 1990 and 8 000 GW at the beginning of the twenty-first century.

Thus the contribution of nuclear energy to the total would, on these forecasts, increase from 2.5 per cent at present to about 50 per cent at the turn of the century. By that time, it is anticipated that most of the new generating capacity being installed will be nuclear, and this is likely to amount to about 400 GW per year. If these forecasts are anywhere near right, it would mean that the equivalent of one new nuclear power station of 1 GW capacity would be completed somewhere in the world *each day*.

There is, of course, a rough correlation between energy consumption per head of population and standard of living. Since the world's population is expected to be double its present size by the end of the century,** an eight-fold increase in energy production in the same period would correspond with a four-fold increase in the global *average* living standard. Since living standards in the underdeveloped two-thirds of the world are at present

* *GW = gigawatt = 10^9 watt.*

** *Most estimates put the present world population in the range* 3 500 *to* 3 700 *million and the population at the end of the century in the range* 7 000 *to* 7 500 *million.*

ten to twenty times lower than in the developed one-third* (see following page), a four-fold rise in the global average would be quite modest.

Parallel with the expansion of nuclear-electrical energy, the cost of *generation* is expected to fall from its present level of around $£2 \times 10^{-3}$ per kWh to half that amount by 1980 and a quarter by the end of the century.

At this price—$£5 \times 10^{-4}$ per kWh—electricity would be as cheap as the cheapest now available in a few very isolated hydroelectric sites, such as Rjukan in Norway.

If such expectations were to be fulfilled, vast perspectives would be opened out. Sea-water could be distilled in vast quantities by the same nuclear power installations that generate the electricity. Urban, and possibly agricultural requirements for fresh water, could be met in this way. Fixed nitrogen could be produced from the air by the electric arc process at a cost comparable to that of the Haber-Bosch process. In addition to fixed nitrogen, potassium salts and phosphates are needed for fertilizers. Potassium salts could be extracted from the sea as a by-product of a sea-water distillation plant, and 'superphosphate' is already being produced from raw phosphate rocks by electrical methods.

According to Alvin Weinberg,** with electricity at $£5 \times 10^{-4}$ per kWh, 'and using as raw material only air, sea-water and phosphate rock, we could probably produce fertilizer that is only 50 per cent more expensive than the cheapest fertilizers now available. Moreover, this source of fertilizer is essentially inexhaustible. In this sense, cheap electricity could indirectly supply sufficient food to keep up with the population, at least for a considerable time.'

Weinberg goes on to speculate about how cheap electricity could be used to make metals:

'All the important metals appear in nature as oxides, the metals having lost their valence electrons. To obtain metals from ores, one must supply electrons. In the smelting of iron ore, electrons are supplied by coke. In principle, electrons can be supplied directly by electricity, or less directly by hydrogen, which is produced from the electrolysis of water. The direct

* *Estimates quoted in the U.N. Statistical Yearbook* (1969) *of the per capita gross national product (GNP) at market prices permit the following comparisons to be made:*

Region	Per capita GNP in 1965 (U.S. dollars)	
	Range	Average
Africa	39 – 780	150
Latin America (excluding Cuba)	85 – 1 159	390
Asia (excluding China and Japan)	67 – 569	120
Western Europe	408 – 2 708	1 587
North America (Canada and U.S.A.)	2 461 – 3 578	3 476
TOTAL, DEVELOPED REGIONS		2 070
TOTAL, UNDERDEVELOPED REGIONS		170

Per capita GNP is, strictly speaking, an indicator of the per capita production of goods and services, and not a direct measure of standard of living. It is nevertheless used as a rough *guide to relative living standards. More accurate comparisons must take into account inequality of distribution of the GNP as between different classes or races in the population of each country.*

** *Alvin M. Weinberg*, Reflections on Big Science, *Pergamon Press*, 1967. *The quotation is from the first of the essays in the book. You have already come across some of the ideas from the third essay in Weinberg's book—'On criteria for scientific choice'.*

cost of the energy is negligible; at 1.5 mills/kWh,* the cost of energy would still add only about two tenths of a cent to the price of a pound of iron. Unfortunately, the needed technology for direct reduction of iron is not developed (although electrolytic reduction of aluminium is a well-developed art). However, electric furnaces in which electricity supplies heat to a mixture of low-grade coke and iron ore have been used to reduce iron ore on a fairly big scale. The advantage of such furnaces is that they use a low-grade, generally abundant coal rather than the high-grade coking coal needed for blast furnaces.'

So much for the promises of cheap nuclear power. What of the perils?

A nuclear reactor producing electricity at the rate of 1 GW produces about 10^{20} new radioactive nuclides per second. Most of these are short-lived, but some have long half-lives and take a very long time to reach equilibrium. After six months' operation, the activity in such a reactor is estimated to be about 7×10^9 curie.** So the activity of the world's nuclear reactors at the end of this century would, if the forecasts quoted above are right, be 4 000 times greater, i.e. about 3×10^{13} Ci.

the curie

What fraction of this activity could be absorbed by the world's population without danger to health? This kind of question is not easy to answer. Some of the problems of estimating quantitatively the biological effects of radiation are mentioned in Appendix 2. As a rough guide, however, we could take the recommendation of the International Commission on Radiobiological Protection (ICRP), that the concentration of strontium 90 (^{90}Sr) in the atmosphere should not exceed some 5×10^{-12} Ci per m^3.*** As you will see if you read Appendix 2, ^{90}Sr is one of the more important radio-isotopes produced in the fission of uranium. It has a half-life of about 30 years. It is estimated that the ^{90}Sr activity after one year's operation of a 1 GW reactor is about 2.5×10^6 Ci, and that by the year 2000, the annual increase of ^{90}Sr will be about 10^{10} Ci. Even if we assume that there is no further increase in nuclear power production beyond the 4 000 GW level, the ^{90}Sr activity would nevertheless reach an equilibrium value of some 4×10^{11} Ci.

Can you make an order of magnitude estimate of what fraction of that activity could be allowed to escape into the Earth's atmosphere without exceeding the ICRP limit?

Six thousandths of a per cent—even if dispersed uniformly throughout an 'atmosphere' 10 km thick—would be a sufficient fraction to exceed the ICRP limit! In practice, an accidental release of radioactive material is likely to produce very much higher local concentrations. In calculations of this kind, the relevant concept is not that of the *whole* population, but of the *critical group* of the population—that fraction which is subject to the greatest degree of exposure as a result of the discharge of radioactive waste materials from a particular site. For instance, in the case of the coastal nuclear energy plants in the UK, the critical group consists most

Take the Earth's radius to be about 6×10^3 km and assume an 'atmosphere' 10 km thick. The volume of this 'atmosphere' is approximately the area of the Earth's surface multiplied by the height of the atmosphere. For a sphere of radius r, the surface area is $4\pi r^2$. So the volume of our 10 km thick atmosphere is

$4\pi \times (6 \times 10^3)^2 \times 10$ km^3 $\approx 5 \times 10^9$ km^3

At a concentration of 5×10^{-12} Ci m^{-3}, or 5×10^{-3} Ci (km)$^{-3}$, such an atmosphere could hold

5×10^9 (km)$^3 \times 5 \times 10^{-3}$ Ci (km)$^{-3}$

$\approx 2.5 \times 10^7$ Ci

So the fraction of ^{90}Sr that could be allowed to escape is:

$\frac{2.5 \times 10^7}{4 \times 10^{11}}$ or $6 \times 10^{-5} \approx 0.006$ per cent.

* 1 *mill* $= 10^{-3}$ *dollars* $= 1$ *millidollar.*

** *One curie* (1 *Ci*) *is the amount of radioactive material in which* 3.7×10^{10} *nuclei disintegrate each second.* (*See section* 3.3 *of Unit* 6.) *This particular rate was chosen because it is close to the rate of disintegration of* 1 *gramme of radium. The unit is named after Pierre and Marie Curie, the discoverers of radium.*

*** *A concentration of* 4×10^{-10} *Ci m*^{3} *in the air would cause a radiation dose, to a person inhaling the air continuously for a year, of* 5 *rad.* (*See Appendix—for a definition of the rad.*) *This is the 'Maximum Permissible Dose' (MPD) recommended by the ICRP for an individual occupationally exposed to radiation. When a whole population is exposed, the recommended dose limit is lower—*2 *rad per generation* (30 *years*), *or* 67 *millirad per year is the current ICRP figure. The corresponding atmospheric concentration of* ^{90}*Sr is thus.*

$$4 \times 10^{-10} \times \frac{2}{5} \times \frac{1}{30} \approx 5 \times 10^{-12} \text{ Ci m}^{-3}$$

frequently of the local fishermen and their families, who eat the greatest amount of locally-caught fish. In addition, the fishermen are subject to external exposure as a result of working on affected beaches, or through the handling of nets contaminated by radioactive silt.

critical group of population

It follows that a monitoring system, such as that operated in Britain by the Fisheries Radiobiological Laboratory (FRL) must in each case take into account the habits of critical groups. Indeed, the FRL goes further than this. In making habit-surveys to 'identify and quantify all pathways leading to public exposure', it takes particular care to ensure that the exceptional person, in respect of eating habits or time spent on potentially contaminated beaches, is not overlooked. Whilst the ICRP now suggests using the mean exposure of the critical group, and not the exposure of the extreme member, the Ministry (of Agriculture, Fisheries and Food) policy continues to take particular account of that person in the group who, by virtue of his habits, is subject to the greatest degree of exposure, and the maximum permissible discharge rate is set by the habits of this person. In this way, no one is likely to be subject to more than the ICRP-recommended dose limit.

disposal of radioactive wastes

Given such stringent monitoring and severe restrictions on the *deliberate* discharge of low-activity wastes from nuclear power plants into the environment, the danger of radioactive pollution is more likely to be in the *accidental* discharge of high-activity wastes.

The problem is in the reactor itself, in the complex chemical plant in which the nuclear fuel elements are processed to separate the uranium and accumulated plutonium from the fission products, and in the system of storing the high-activity fission products over very long periods of time.

Figure 4* illustrates the main steps in the normal nuclear fuel cycle, and the attendant pollution of the atmosphere and the sea (pp. 76–7).

In theory, the fuel elements of a reactor are in sealed containers, so that there should be no escape of radioactivity. In practice, small leaks develop in some of the containers and produce small amounts of pollution.

The chemical separation process is a complicated business and takes place under conditions of remote control. It is very difficult to prevent the escape of some radioactivity. Some of the fission products are gases, like ^{85}Kr (which has a half-life of some 11 years), and it has been estimated that 2.5×10^8 Ci of this isotope would be released by about the year 2000 if present practices continued.

Another gaseous radio-isotope that is released in this way is tritium, the radioactive isotope of hydrogen. At present, the release of these gaseous and low-activity liquid products is planned, that is, it is normal practice to allow them to escape into the environment. It seems very likely that this practice may have to be discontinued when such vast quantities are involved as are implicit in the scale of nuclear energy production forecast for twenty or thirty years' time.

This could lead to substantial increases in the cost of chemical processing and hence, ultimately, to the cost of generated electricity. This sort of consideration could very easily upset some of the more optimistic economic forecasts.

Perhaps the most serious problem is that of storing the long-lived fission products. Various storage systems have been devised. In the UK, the fission products are stored in large stainless-steel tanks. The effluent is initially dissolved in dilute acid, and the solution is then concentrated a hundred-fold by evaporation, and the remaining liquid stored in a tank

* *From an article by Frank Barnaby in* Science Journal, *August* 1970.

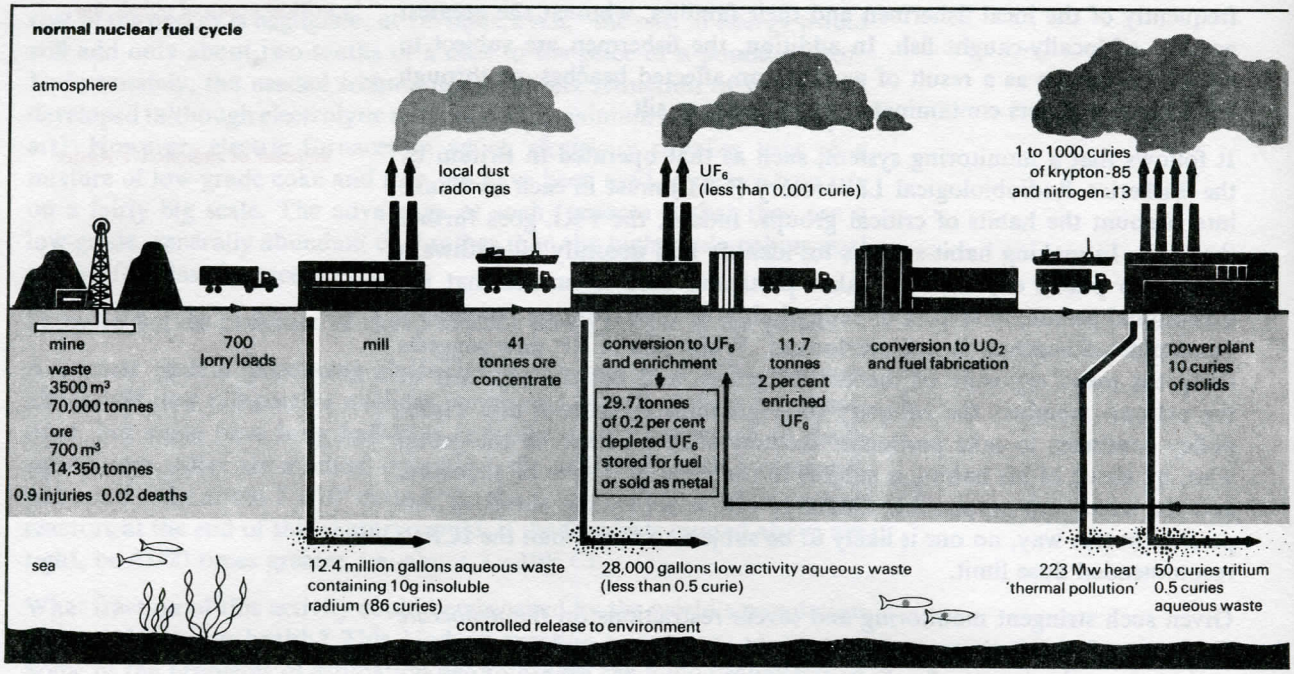


Figure 4 The nuclear feed cycle and attendant pollution.

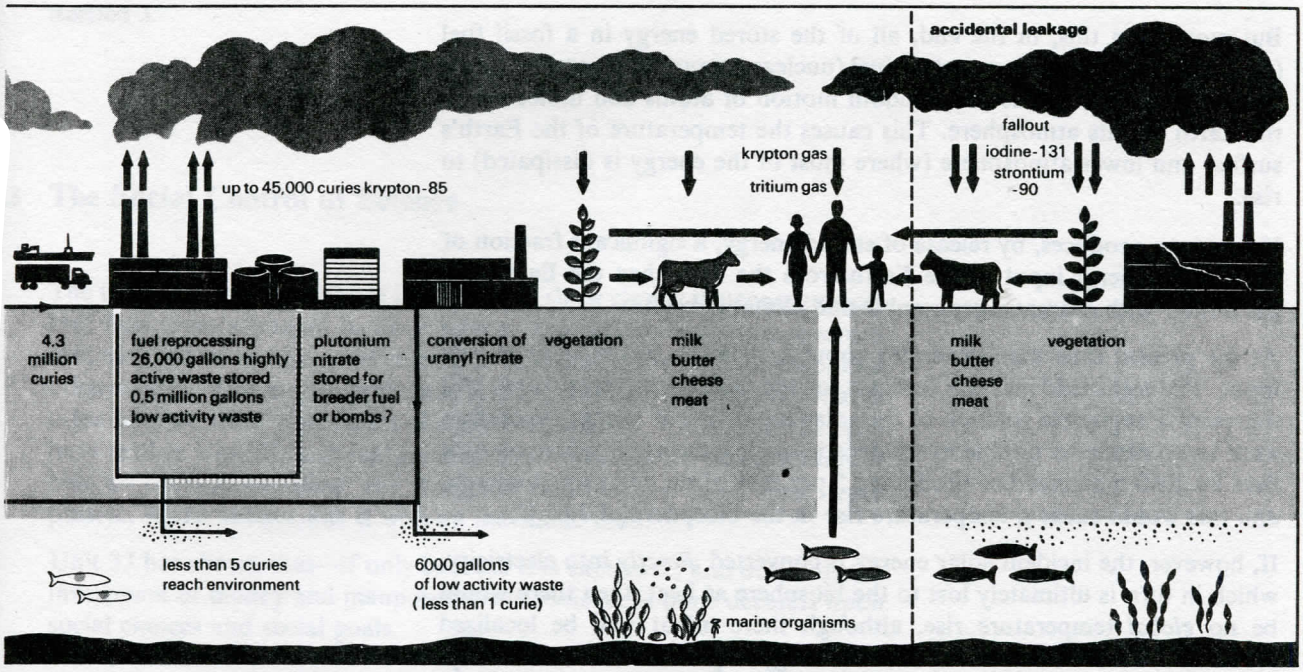
of about 100 m³, which may contain an activity of about 10^8 Ci. There have been no accidents with this system in the course of 20 years, but the products will have to be stored for hundreds of years for safety.

At Oak Ridge, Tennessee, radioactive wastes are mixed with cement and 'pumped 1 000 feet into the ground, there to set permanently along fracture planes between beds of rock. As nearly as geologists can determine, these sheets of radioactive concrete will remain completely out of contact with the biosphere until long after their radioactivity has decayed'.*

Other systems of waste disposal include chemical treatment to produce water-insoluble compounds which are then enclosed in stainless-steel vessels and dumped in deep ocean trenches. Disused salt mines are used in some countries for storage of radioactive waste materials. In other cases, the waste is stored in specially built concrete vaults. All these systems seem to have very low probabilities of failure. But, as the total amounts of material to be stored increase towards the fantastic giga curie levels currently forecast, even such low probabilities may become too high to accept.

A somewhat similar consideration applies to the risk that a major accident to a nuclear reactor might cause the unplanned release of radioactivity into the environment. Very elaborate safety precautions are incorporated to prevent reactors from getting out of control, though a few minor accidents have already taken place. (One of them is mentioned in Appendix 2). It is, for example, somewhat dangerous to have a reactor situated in an earthquake area. Although the probability of serious accident is calculated to be less than one in one hundred thousand, it is very difficult to persuade insurance companies to insure reactors. In the United States, for example, the Atomic Energy Commission, the Government body, has itself had to assume the role of insurance company. Further possibilities of accidents in nuclear power production arise in the transportation and handling of fuel elements in their journey from the reactor to the processing plant. It is an unfortunate fact that processing plants are often at some distance from reactors and the possibilities of accidents cannot be dismissed.

* *Alvin Weinberg*, Reflections on Big Science.



In spite of all this, Alvin Weinberg's confidence that technological solutions will be a step ahead of technological problems remains unshaken. He writes:

> Generally, I am extremely optimistic about dealing with our nuclear garbage, so much so that I believe nuclear plants will displace fossil fuel plants not only because they are cheaper, but also because they are cleaner.

In evaluating the potential pollution of the environment by nuclear power stations, we ought not to overlook the actual pollution by thermal power stations. A coal-fired station generating 1 GW emits about 250 tons of sulphur dioxide per day into the atmosphere, as well as appreciable amounts of radium.

The production of energy from the controlled fusion of deuterium (Unit 31) would reduce the problem of radioactive pollution by a large factor. A thermonuclear reactor may nevertheless constitute a considerable radioactive source, as the fusion reactions involve the production of fast neutrons and these in turn would make the shielding material around the reactor highly radioactive. The fundamental problem of containing a quantity of ionized deuterium or tritium at a temperature of around a million degrees for long enough to allow the fusion reaction to develop has not yet been solved, in spite of considerable efforts.

In the long run, neither fossil fuels, such as oil or coal, nor nuclear fuels, such as uranium, thorium or (if thermonuclear reactors eventually prove practicable) deuterium, can be regarded as satisfactory sources of energy. This is not only because they are all liable to cause environmental pollution, by releasing noxious materials into the biosphere.

There is a more fundamental problem caused by all systems that release energy stored at some time in the past history of the Earth. It is the problem of *thermal pollution*. All systems of power generation waste heat which is discharged into a convenient river or lake (Fig. 4). This can upset the ecological balance of the water system, sometimes with serious consequences. This problem of *local* thermal pollution is receiving greater attention as the consequences become better understood.

thermal pollution

But more than this, in the end, all of the stored energy in a fossil fuel (chemical energy), or, in a nuclear fuel (nuclear energy) is eventually transformed into heat, that is into random motion of atoms and molecules in the Earth and its atmosphere. This causes the temperature of the Earth's surface and lower atmosphere (where most of the energy is dissipated) to rise.

If ever man produces, by release of stored energy, a significant fraction of the average energy input to the Earth from the Sun, then the Earth will get hotter, with dramatic geographic and climatic results.

At the present time man generates about 1/10 000th of the solar energy input. The eight-fold increase forecast for the next thirty years would still represent a negligible fraction of the solar input. But if energy generation were to continue to double every decade during the twenty-first century then by 2060 man *could* be producing 5 per cent of the solar input energy, and this would cause a temperature rise in the biosphere of 3.5° C.

If, however, the incident solar energy is converted *directly* into electricity, which in turn is ultimately lost to the biosphere as heat, then there would be no *global* temperature rise, although there might well be localized effects. It is for this reason that man's energy requirements in the twenty-first and later centuries will have to be provided by some form of direct solar energy converter.

Looked at in this context, nuclear energy must be seen as a purely temporary device, bridging the gap between the fossil fuel era and the solar energy transformation era. In historical terms, the atomic age is likely to be rather short. Even so, it will be long enough to tax to the limit man's ability to adapt in order to survive. Since the adaptation required involves no less than the elimination of global war and the establishment of far-reaching international controls over the peaceful applications of nuclear energy, the process of adaptation must clearly take place at the social level—that is, at the highest level of organization and complexity with which science, and this Foundation Course in science, is concerned.

Summary

The first large-scale application of nuclear energy was for a specific military-political purpose. In the first fifteen years after Hiroshima, the military application continued to dominate the nuclear energy programme. Since about 1962, however, the peaceful application—to the generation of electrical energy—has been developing much more rapidly, and the installed capacity of nuclear power stations is expected to increase from about 2.5 per cent of total installed capacity at present to about 50 per cent by the end of this century. Generating costs are expected to fall, over the same period, from $£2 \times 10^{-3}$ per kWh to less than $£5 \times 10^{-4}$ per kWh. Whereas the availability of such cheap electrical energy would open up many new possibilities for providing the world's population with food, water, and other essential materials, the application of nuclear energy on such a vast scale would create immense problems in the safe disposal of radioactive waste products and in the safe operation of so many very large nuclear power stations.

In the long run, the problem of global temperature rise is likely to set a limit to the amount of stored energy that can be released into the biosphere, whether from fossil or nuclear fuels. In historical terms, the atomic age is likely to be short, but crucial to man's survival.

34.3 The Social Control of Science

The two case studies you have just followed show clearly the consequences that flow from advances in basic science and technology—consequences that may indeed have seemed remote to the scientists who made the initial observations. You may regard these studies, then, as examples of what is often referred to as 'the impact of science on society'. Yet, from what you have read in Unit 33, it should be clear to you that such a description is at best an oversimplification, for it implies that 'society' is in some sense passive, whilst science hits it with an inevitable thud.

Unit 33 has shown that—if only because it is expensive, and demands the investment of money and manpower—what science is done depends upon social choices and social goals.

What were the social goals involved in the initiation of the large-scale applications of the nitrogen-fixation techniques and of nuclear chain-reactions?

In the first case, the need for fertilizers and explosives by Germany during the 1914–18 war; in the second, the need to build an atomic bomb in the United States in the 1939–45 war.

Thus, in both cases, the scientific and technological developments involved were consequences of particular social goals. This is why we categorized these case studies as examples of the consequences of the deliberate exploitation of science, rather than as casual or accidental or unforeseen, although in both case studies you will note that some of the consequences, at least, were not part of the original bargain, so to speak. It would have required considerable foresight to have predicted that one consequence of the development of the Haber process would be that the eutrophication of Lake Erie would be speeded up, or that the work of Rutherford, Hahn, Meitner, Bohr, Joliot-Curie and the other physicists of the 1930s would result in an increase in the incidence of leukaemia caused by radiation.

Nonetheless, the major intentions of society, in investing money in either the Haber process or the Manhattan Project, fixed nitrogen and nuclear power respectively, were met. This gave rise not only to large-scale changes in society—the lives of everyone on Earth have been changed by both developments—but also to new scientific problems, interests and developments. Scientific problems do not occur in the abstract, but derive from the existing interests of science and the social setting in which it is performed. So the goals of society determine in some measure the sort of science that is being done. You saw this in global terms in Table 4 of Unit 33. What this means for particular scientists is shown in the television programme of this Unit. There, you see government, industrial and university scientists discussing the constraints on their work and what directs their choice of problems and research. In each case, the choice is based partly upon the intrinsic interest of the subject itself, partly upon the extrinsic constraints of obtaining funds and support for particular projects, which are governed by non-scientific criteria—welfare, profitability, or military needs.

We can sum up all these complex relationships in terms of a three-fold interaction between the internal logic of the science itself, the demands and possibilities of technology, and the external demands and pressures, both economic and ideological, of society.

Of course, not everyone would accept that this was an accurate picture of

these relationships—remember that in discussing these topics we are in an area in which 'right' and 'wrong' answers are not as obvious as they, hopefully, were in that part of this Course which dealt with the internal content of science. There are those, for instance, who argue that because a particular piece of science or technological development is possible, it becomes inevitable that it *has* to be done irrespective of the consequences; that because hydrogen bombs, antiballistic missiles, genetic engineering or supersonic airliners are possible, then it is inevitable that they will eventually be developed. Such a view is best summed up in the well-known phrase of the American physicist J. Robert Oppenheimer, one of the leading scientists of the Manhattan project, who had initially doubted the possibility of making hydrogen bombs until the technical 'fix' that would do the job was provided by another physicist, Edward Teller. Oppenheimer's opposition disappeared, 'It was technically sweet'; he is later quoted as having stated, 'we had to go ahead and do it'.

the technological imperative

This view of the technological imperative ignores the fact that the H-bomb project was also to cost very large sums of money to go ahead and do it—money which had to be provided by a willing US government.

If, therefore, the sort of science that gets done in a particular society is not inevitable—nor inevitably the most desirable—it follows that the social choices which determine what science is done need careful scrutiny. This was the point of the decision-making kit of Unit 33. How can it be ensured that scientific choices are made democratically and in the best interests both of the community as a whole and of science? You will see some of these issues raised in the last part of the television programme of this Unit, and a 'talk-back' continues the debate in the radio programme. One point of view—not necessarily the only one—is expressed in *Science and Society*, pp. 261–72, which you may read if you wish.

34.4 The Question of Responsibility

What conclusions can be drawn from the brief study of Science and Society in these last two Units of the Course, or, indeed from the Course as a whole?

In this Course, you have sampled some of the most important aspects of contemporary science. In most cases you have noted only the essential points and have moved on without going into details. Every now and again you have paused and taken a closer look. The Course has thus been, not a *survey* but a *sampling* of science. We hope it has given you some insight into the inner logic and method of science, and into its extraordinary fascination and intellectual beauty. You will have seen how science has advanced through a complex interaction between theory and experiment. This is the *internal* dialectic of science. But neither the content of science nor its form, still less its history, can be understood in terms of this internal interaction alone. The external interaction, between science and society, is an essential aspect of the whole process of scientific advance.

This has been true throughout the history of science, but the external interaction of science has become much more important in the present century than it ever was in the past. In the eighteenth century, science was in the main a peripheral activity and had negligible effects on society, although society did not have negligible effects on science. But by the twentieth century, science has become a major factor shaping society and determining its future—possibly even its survival. Science now consumes a significant and increasing proportion of social resources, both material and human.

In this situation, it is no longer realistic for a scientist to ignore the social context and consequences of his work. The social context determines, directly or indirectly, the resources he will have at his disposal, the choices that will be open to him to make and the problems that he seeks to solve. The social consequences of yesterday's science may now include the survival of today's science—and today's scientist.

Nor can society afford much longer to regard science—and technology—as something 'inevitable', like the weather, something beyond the comprehension and control of the common man.

The realities of the situation, of science, and of society are such as to raise in a new and sharp way the question of *responsibility*.

responsibility

For the scientist, this means a responsibility to be aware of the possible consequences of his own work, to consider carefully the extrinsic as well as the intrinsic merits of the choices that are open to him, and to be conscious of the social factors that limit those choices. Above all, it means *a responsibility to inform society* of the implications of the existing and foreseeable scientific and technological options. In a democratic society, this means informing the public.

Corresponding to the scientist's responsibility to society, there must be a responsibility of society for science. For the individual member of society (including the individual scientist), this means a responsibility to be aware of what science is, what it can do—and what it cannot do,

to understand the relations between science, technology and society, and to act politically to ensure that science is used for the good of society as a whole.

Whether you approach the question of responsibility in science from the viewpoint of the scientist's responsibility to society or from the viewpoint of society's responsibility for science, you arrive at the same central point—that of information.

It is here that the scientist has a special responsibility—to make the meaning and implications of scientific discovery comprehensible and clear to the non-specialist public. It is high time for the traditional contempt for 'popularization' to be discarded. The 'flight from science' and the anti-scientific philosophies that have proliferated in recent years* should serve as a warning that science can no longer take social esteem for granted.

Clearly, education has a vital role in all this. If society is to be able to solve the problems already posed by science and to enjoy to the full the benefits that science can bring, then it must achieve a much higher general level of scientific education. This education must start at the primary school level and continue through the formal education process and in everyday life. As science itself is in a state of rapid development, scientific education—and scientific educators—are in constant danger of becoming out of date.

It is at least partly for this reason that the Science Foundation Course you are just completing will be rewritten in four years' time. By then, some 20 000 Open University students will have studied it, and almost 5 000 of these will be school teachers. It will, we hope, have had some small, but not negligible effect.

* *Among the more serious writers in this vein, Jacques Ellul and Theodore Roszak may be cited.*

Appendix 1

The Chemistry of the Haber Process

The essential process is expressed in the equation

$$N_2 + 3H_2 \rightleftharpoons 2NH_3 \qquad \Delta H = -109 \text{ joules at } 550^\circ \text{ C}$$

What does the double arrow symbol signify?

Is the reaction exothermic or endothermic?

(Unit 11, section 11.4.1.)

The reaction is an equilibrium reaction and is exothermic. At room temperature the reaction proceeds so slowly that it cannot be observed, the nitrogen and hydrogen do not appear to combine neither does ammonia show any signs of decomposing. Even at high temperatures (500° or more) the rate of attainment of equilibrium is very slow except in the presence of a catalyst.

Will a catalyst affect the *position* of equilibrium? (By position of equilibrium is meant the concentrations of all the components of the reaction mixture when the mixture is *at* equilibrium.)

(Unit 12, section 12.4.2.)

However, the fact that the reaction is exothermic introduces an additional complication. In Unit 12, section 12.4.1 it was pointed out that the way an equilibrium constant varies with temperature depends on the sign of ΔH^θ in a manner that can be predicted using Le Chatelier's principle (Unit 9, section 9.20).

Can you recall Le Chatelier's principle?

It states that when a system in equilibrium is subjected to an external constraint, the system reacts to lessen the effect of the constraint.

In an exothermic reaction (ΔH^θ negative) heat is given out, so that the reaction will be favoured if this heat can be removed, that is if the system is cooled. In this ammonia-formation reaction the position of equilibrium will shift to the right (→), that is in favour of the formation of ammonia, if the reaction mixture is cooled.

So a compromise has to be reached between an acceptable rate of formation of ammonia, which requires high temperatures, and an acceptable position of equilibrium which requires low temperatures.

Can you predict what the effect of increase of pressure would be on the position of equilibrium?

In Unit 5, section 5.3.3, you learned of Avogadro's hypothesis 'that equal volumes of all gases, under the same conditions of temperature and pressure, contain the same number of molecules'. A direct deduction from this hypothesis is that a mole of any gas must always have the same volume. (This volume at 0° C and 760 mm pressure is 22.4 litres.)

For the ammonia equilibrium reaction then, the volume on the left-hand side of the equation must be twice that on the right-hand side.

$$N_2 + 3H_2 \rightleftharpoons 2NH_3$$
1 vol 3 vols 2 vols

Now apply Le Chatelier's principle. The system reacts to lessen the effect of the constraint—in this case the increased pressure—that is, the position of equilibrium moves in favour of the formation of ammonia.

Again, however, one is faced with the need for compromise for while an increase in pressure favours the formation of ammonia (and indeed because increase of pressure amounts to an increase of concentration, the rate at which equilibrium is attained), working on an industrial scale at high pressures involves engineering and technical problems.

In practice then the Haber process represents a series of informed compromises based on data obtained from many thousands of experiments. (L. F. Haber, the son of Fritz Haber, in his booklet *The Nitrogen Problem*, reports that by 1912 some 6 500 experiments had been carried out in order to find the best cheap effective catalyst for the reaction.) Usually the reaction is carried out at a temperature between 350–600° and a pressure of 150–350 atmospheres in the presence of an activated iron catalyst containing potassium, aluminium and calcium oxides.

The choice of the catalyst is critically important and the discovery of a more active catalyst could have dramatic repercussions. If the reaction could be induced to proceed rapidly at room temperature or below, the yield would be increased because the equilibrium would be shifted in favour of ammonia. Now the mechanism by which the nitrifying bacteria fix nitrogen is unknown—it obviously involves molecular (gaseous) nitrogen and equally does not involve molecular hydrogen—but it does involve a reaction of molecular nitrogen at temperatures around 10–30° and at atmospheric pressure. For this reason much research effort is currently being directed to examine systems to act as models for the biological fixation process.

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The Biological Effects of Ionizing Radiation

Ionizing radiations

During this Course you have already come across the major forms of ionizing radiation. In Units 6 and 30 you met α, β and γ radiation and in Unit 3 you learned about neutrons and neutron beams. You will remember that α-rays are helium nuclei, β-rays are electrons (or positrons) and γ-rays are high-energy photons.* In the remainder of this Unit, when we talk about γ-radiation without qualification we shall include X-radiation, another ionizing electromagnetic radiation though of longer wavelengths (Unit 28). Neutrons, produced in great numbers in nuclear reactors (Unit 31), are a major industrial source of ionizing radiation. There are in addition other sources of ionizing radiation mostly arising in scientific experiments or in therapeutic apparatus.

In the former category, beams of protons and electrons, produced by particle accelerators, are the most common. The energies of such artificially produced ionizing particles range from a few MeV to many GeV, and, as you have seen in Unit 32, they produce a large variety of secondary particles, such as pions and muons, some of which are electrically charged and can therefore produce ionization. The intensities of such particle beams from accelerators are often very high indeed, and (as you saw in the TV programme of Unit 32) stringent safety precautions are necessary to protect personnel from exposure to such radiation.

Therapeutic apparatus, in which ionizing radiation is used for the treatment of cancer, most typically uses either X-rays or electron beams from accelerators in the 1 MeV to 30 MeV range, or γ-rays (of 1.3 MeV energy) from a 'cobalt-60 source'.**

therapeutic apparatus

The β-rays emitted in radioactive decay have energies in the range of, typically a few KeV to a few MeV (<4 MeV).

All ionizing radiations lose energy in their passage through biological tissue, by processes which produce ion pairs either as a primary or as a secondary effect. The major component of all biological tissue is water (Unit 5), which accounts for up to 70 per cent of the body weight of a mammal.

In water, the overall effect of an ion pair production can be represented

$$H_2O + \text{energy} \rightarrow H^{\cdot} + OH^{\cdot}$$

where $H^{\cdot}$ and $OH^{\cdot}$ are called 'free radicals' and are not the same as the normal H^+ and OH^- ions; they have different electron configurations (Unit 7) and are much more reactive chemically. It is these free radicals (or ion pairs) which are the sources of the biological effects of ionizing radiations.

The major differences between the ionizing radiations from the biological point of view are concerned with their range in tissue, that is with the

* *Electromagnetic waves of very short wavelength.*

** *This consists of a small capsule of ^{60}Co (a radio-isotope with a half-life of 5.2 years which decays through the emission of γ-ray photons and an electron to ^{60}Ni) enclosed in a thick lead shield with a suitable aperture to collimate the γ-ray beam. Therapeutic cobalt-60 sources usually have a strength of about 4 000 to 5 000 curie. The curie was defined in section 3.3 of Unit 6.*

depth to which they will penetrate into tissue and with the way in which they form free radicals, and thus lose energy, along their paths. These things can sometimes be studied in simulated situations using cloud-chamber techniques (which you have met in passing in Units 2 and 31) and they can sometimes be dealt with theoretically by calculation from known data about ionizing radiation and the density and composition of tissues.

We need a measure of the amount of energy absorbed by the living tissue under consideration—that is, a measure of radiation 'dose'. In the early days of X-rays, a unit called the *röntgen* was established. This unit (called after the discoverer of X-rays) was defined as the amount of X-radiation which will produce 2.08×10^9 ion pairs in 1 cm^3 of air; it was convenient practically, since the ionization could be measured directly with the simple ionization chambers then in use.

the röntgen

It is known that to produce each ion pair in dry air requires about 33 eV, and so the energy required for 2.08×10^9 ion pairs is 6.77×10^4 MeV, which corresponds to an energy absorption of 1.08×10^{-9} J cm^{-3}.* The density of dry air (at 0° C and one atmosphere) is 1.29×10^{-6} kg cm^{-3} so the energy absorption *per kilogramme* is $\frac{1.08 \times 10^{-9}}{1.29 \times 10^{-6}}$ J kg^{-1} or about 0.84×10^{-2} J kg^{-1}.

In tissue or water the absorption is about 0.97×10^{-2} J kg^{-1}. Thus, a röntgen could be defined as the amount of X-radiation that produces absorption in tissue of 0.97×10^{-2} J kg^{-1}.

Later it was realized that a satisfactory unit for radiation dose should be universally applicable to all ionizing radiations, unlike the röntgen which applied to X-rays only. A new unit was defined, the 'rad', which is now the preferred unit for radiation dose. One rad is the radiation dose which will result in an energy absorption of 1.0×10^{-2} J kg^{-1} in the irradiated material. Numerically you will see that for X-rays the röntgen and the rad differ by only a few per cent, normally within the experimental error.

the rad

The penetration of ionizing radiation into tissue

The different sorts of ionizing radiation penetrate to greatly different extents into tissue and this is part of the reason for the different biological effects which they produce. α- and β-radiation (from radioactive decay) cannot penetrate very far into tissue, so that the effect of α- or β-radiation, unless of high energy, is mainly confined to the surface of the organism (assuming that it comes from an external source). However, it is possible to have isotopes producing α- or β-radiation within the organism itself. This can happen either through ingestion in food and deposition at various points in the organism or it can happen through injection when radioactive isotopes are used in biological tracer experiments.† In either case, selective local depositions of specific isotopes can occur and then the local dose of α- or β-radiation within the organism, possibly deep within the organism, can be very high indeed. This is for example the basis of the leukaemia producing effect of ^{90}Sr, one of the isotopes which we are concerned with in this Unit.

In contrast with the short range in tissue of the α-particles or the low energy β-particles emitted by radioisotopes, X-rays, γ-rays, and neutrons can penetrate very much more deeply. As a result, the dose to an organism from any of these more penetrating radiations is likely to be a 'total body dose'—it is likely to extend throughout a large part of the organism.

* *Remember that an electron volt is a measure of energy, which could also be measured in joule. One electron volt is* 1.6×10^{-19} *joule.*

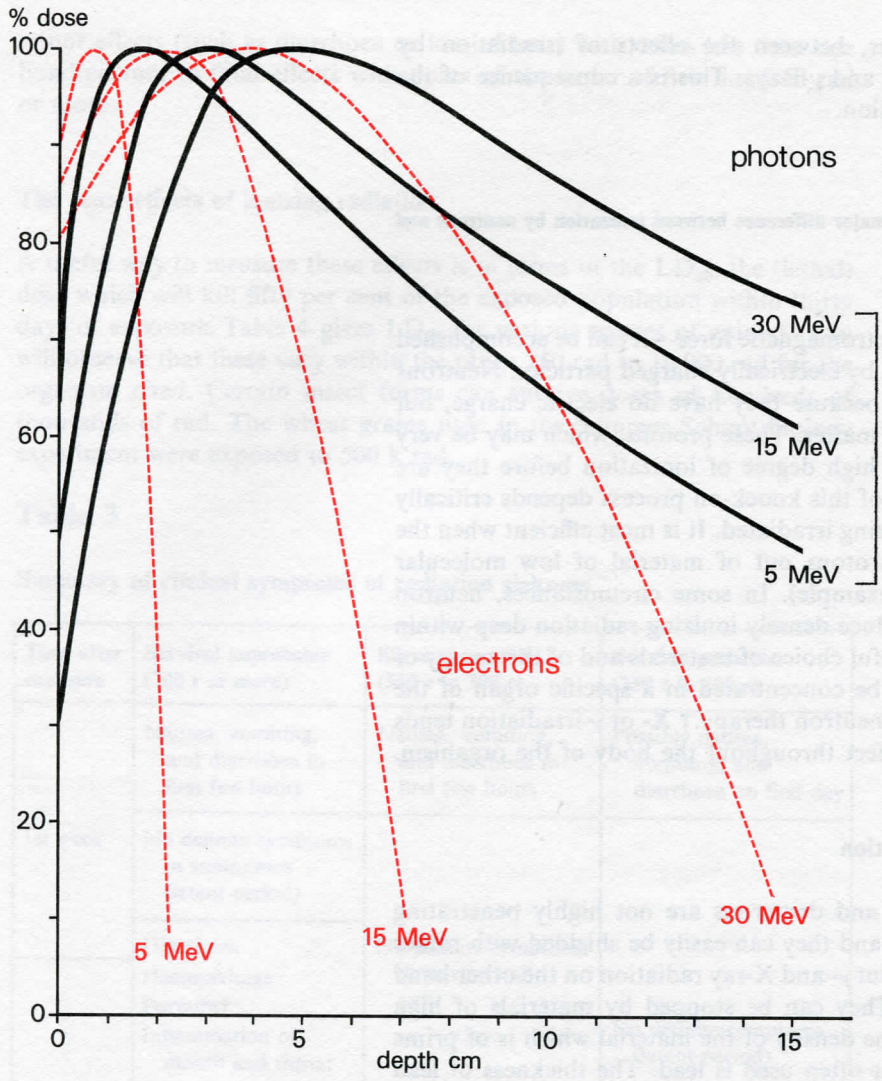


Figure 5 Comparison of the dose-depth effects of photons and electrons.

The difference between the ionization produced in tissue by electrons and photons (X-rays or γ-rays) of the same energy is shown in Figure 5. When photons pass through matter they eject secondary electrons which then ionize the matter through which they pass. These secondary electrons have energies comparable to those of the original photons, so you might expect a directly applied electron beam to have similar biological effects to a photon beam. This is indeed the case, but, as you can see from the figure, there is a significant difference in the dose-depth characteristics.

Photons of the relatively low energy of 5 MeV still produce 50 per cent of the maximum dose (i.e. 50 per cent of the maximum number of ion pairs per cm^3) at a depth of 15 cm. Even at a depth of 30 cm the dose is still 20 per cent of maximum. Contrast this with 5 MeV electrons, for which the dose is zero at depths greater than 2 to 3 cm.

The 5 MeV photons produce secondary electrons *all the way through* the tissue, and these are rapidly slowed down and stopped within a few cm of where they were produced.

The sharp cut-off of the electron dose curves is of practical importance in the use of electron beams for cancer therapy—for instance, in cases where the tumour extends from just below the surface down to a point beyond which it is important to avoid any appreciable irradiation.

At lower energies, the contrast between X-rays and electrons is even more marked. At 1 MeV, for instance, X-rays produce their *maximum* dose at a depth of 2.5 mm—but the dose is still about 50 per cent of maximum at a depth of 10 cm. With 1 MeV electrons, however, *all* the ionization is produced within the few millimetres nearest the surface, and the dose is zero at greater depths.

There is a difference, however, between the effects of irradiation by neutrons and the effects by X- and γ-Rays. This is a consequence of the different mechanisms of ionization.

What do you think is the major difference between ionization by neutrons and X or γ photons?

Ionization is an effect of the electromagnetic force—it can be accomplished by electromagnetic quanta and by electrically charged particles. Neutrons cannot ionize matter directly, because they have no electric charge, but they can knock protons out of matter. These protons, which may be very energetic, will then produce a high degree of ionization before they are brought to rest. The efficiency of this knock-on process depends critically on the nature of the material being irradiated. It is most efficient when the neutrons are able to knock protons out of material of low molecular weight (water is an obvious example). In some circumstances, neutron irradiation can be used to produce densely ionizing radiation deep within the irradiated material. By careful choice of materials and of the energy of the neutrons these effects can be concentrated in a specific organ of the body, and this effect is used in neutron therapy.† X- or γ-irradiation tends to produce a more uniform effect throughout the body of the organism.

Shielding against ionizing radiation

α-particles, electrons, protons and deuterons are not highly penetrating unless they are of high energy and they can easily be shielded with rather small thicknesses of material. But γ- and X-ray radiation on the other hand are much more penetrating. They can be stopped by materials of high atomic number, because it is the density of the material which is of prime importance. The material most often used is lead. The thickness of lead used will, of course, depend on the energy of the photon, but will vary from a few millimetres with low-energy X-rays used in X-ray diffraction to several inches of lead in the case of X-ray photons of several MeV used in deep therapy.†

deep therapy

With neutron irradiation, the shielding effect of a material depends on the number of nuclei in the path. Neutrons lose energy by knocking protons on and therefore they will be stopped most efficiently (as you will remember from Units 4 and 5) when they are presented with many nuclei of roughly the same mass as the neutrons themselves. It is for this reason that water is a very efficient stopper of neutrons, as it has large numbers of hydrogen nuclei roughly the same mass as the neutrons. In fact, a layer of water will stop neutrons better than an equally thick layer of lead, while for X-rays the lead would be twelve times more effective.

Concrete is often used for shielding against neutron radiation. Fast neutrons are very difficult indeed to shield effectively and must be regarded as a very dangerous form of atomic radiation. This is particularly so in a situation where high doses of fast neutrons are produced quickly in unexpected circumstances. This happens when a nuclear weapon explodes, and certainly at close ranges, the neutron irradiation effect is very deadly.

The effects of ionizing radiation on an organism

The effects of ionizing radiation on an organism can be divided generally into three parts: the acute effects, the longer-term effects and the genetic effects. The acute effects are summarized in Table 3. They clearly depend on the dose received to the whole body and vary from comparatively

minor effects (such as diarrhoea or loss of hair) with doses less than one hundred rad, to fatal effects with doses of the order of five hundred rad or more.

The acute effects of ionizing radiation

A useful way to measure these effects is in terms of the LD_{50}, the (lethal) dose which will kill fifty per cent of the exposed population within thirty days of exposure. Table 4 gives LD_{50} for various species of animal. You will observe that these vary within the range 250 rad to 10 000 rad for the organism cited. Certain insect forms can survive doses of hundreds of thousands of rad. The wheat grains used in the Summer School biology experiment were exposed to 500 k rad.

LD_{50}

Table 3

Summary of clinical symptoms of radiation sickness

Time after exposure	Survival improbable (700 r or more)	Survival possible (550 r to 300 r)	Survival probable (250 r to 100 r)
1st week	Nausea, vomiting, and diarrhoea in first few hours	Nausea, vomiting, and diarrhoea in first few hours	Possibly nausea, vomiting, and diarrhoea on first day
	No definite symptoms in some cases (latent period)	No definite symptoms (latent period)	No definite symptoms (latent period)
2nd week	Diarrhoea Haemorrhage Purpura† Inflammation of mouth and throat Fever Rapid emaciation Death (Mortality probably 100 per cent)	Epilation† Loss of appetite and general malaise Fever	Epilation† Loss of appetite and malaise Sore throat Haemorrhage Purpura† Petechiae† Pallor Diarrhoea Moderate emaciation
3rd week		Haemorrhage Purpura† Petechiae† Nosebleeds Pallor Inflammation of mouth and throat Diarrhoea Emaciation	
4th week		Death in most cases (Mortality 50 per cent for 450 röntgen)	Recovery likely in about 3 months unless complicated by poor previous health or super-imposed injuries or infections

Table 4

A comparison of some 30 day LD_{50}s for total body dosage of X-rays.

	r
Guinea Pig	250
Pig	300
Goat	350
Dog	350
Man	400
Mouse	550
Monkey	600
Chicken	600
Rat	650
Hamster	700
Frog	700
Rabbit	800
Song Sparrow	800
Tortoise	1 500
Newt	3 000
Snail	10 000

The LD_{50} for man is of the order of six hundred or seven hundred rad.* You may remember from the earlier section that one rad produces an energy absorption of 10^{-2} J kg^{-1}, so the LD_{50} for man produces an energy absorption of 6 or 7 J kg^{-1}. A similar amount of *heat* energy would only raise the temperature of each gramme of the tissue by a few hundredths of a degree centigrade. So you can see that in terms of the energy required, ionizing radiation is a very efficient way of killing people.

The longer term effects of ionizing radiation

A number of consequences to man of nuclear radiation exposure may not appear for several years. Among these are the formation of cataracts, leukaemia and other forms of malignant disease, retarded development of children irradiated in *utero* and general life-shortening. The data on these effects for human beings are necessarily limited. Continuing studies are made in Japan on survivors from Hiroshima and Nagasaki and other studies have been made of workers who have been irradiated in the course of their employment before the dangers were understood (for example, uranium miners in Czechoslovakia).

Because the data are limited, it is very difficult to be specific and quantitative about these effects. Interest has centred on the question of whether there is a threshold dose, that is, can some amount of radiation be specified below which no effect is produced.

** Sometimes another unit is used, the 'röntgen equivalent man' or rem. This is introduced because not all types of radiation are equally efficient in producing specific biological effects, and the dose in rad must be multiplied by some 'biological efficiency' to give the magnitude of the effect. The rem is dose in rad × biological efficiency. For our purposes we shall give doses in rad rather than rem.*

the rem

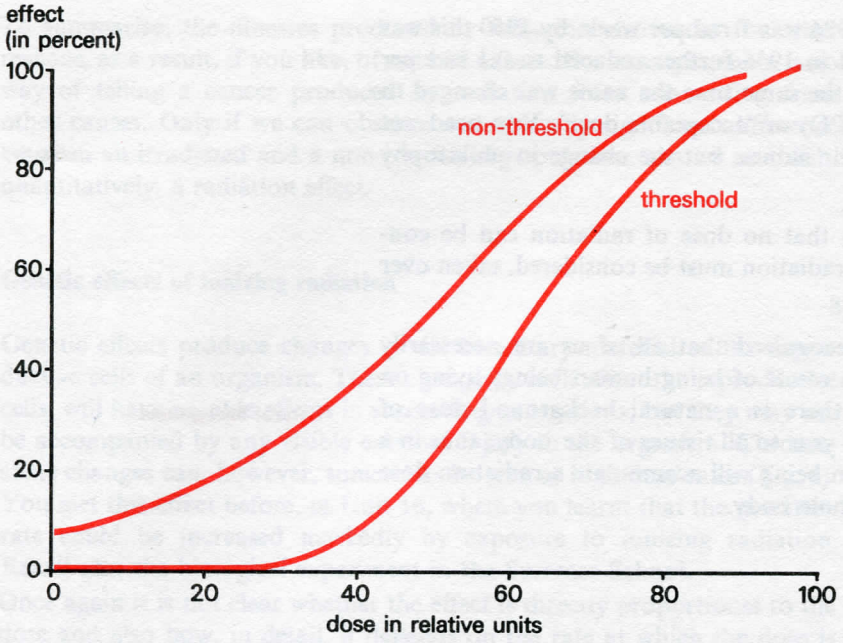


Figure 6 Characteristic curves for threshold and non-threshold effects of radiation.

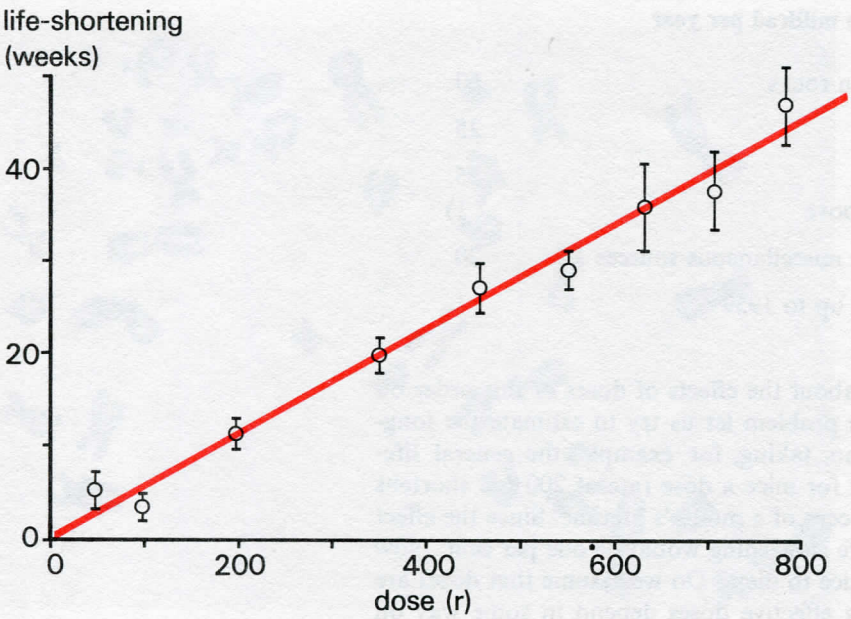


Figure 7 Life-shortening of mice as a function of radiation dose.

threshold and non-threshold dose

The problem is posed in Figure 6, which shows the difference between a threshold dose and a non-threshold dose situation. Much experimental work, mainly with experimental animals, has gone into considering this question and opinion now seems to be generally that there is not a threshold dose for these long-term effects. The work of Lindop and Rotblat,* from which the Figure 7 is taken, shows that for life-shortening of mice the effect is linear down to low dose rates. This is an important question because many codes of protection against radiation, and codes of industrial practice are based on the implicit assumption that there is a minimum dose of radiation below which no harm may be caused.

It is an interesting fact that the so-called safe dose has been continually revised over the years that radiological protection has been known and it has always been revised in a downward direction. The International Commission on Radiological Protection was established in 1928 to consider the problem. Initially the permitted doses were called 'tolerance doses'.

* Proceedings of the Royal Society B, *1961, Vol. 154.*

The tolerance dose accepted in 1934 was 1 rad per week, by 1950 this was reduced to 0.3 rad per week and in 1956 further reduced to 0.1 rad per week (5 rad per year). At about the same time the name was changed to 'maximum permissible dose' (MPD) or 'acceptable dose'. You need not remember all these doses, or their names, but the change in philosophy over the years is interesting.

Currently the general opinion is that no dose of radiation can be considered as safe and that all extra radiation must be considered, taken over the whole population, a bad thing.

At the same time it must be recognized that all of us are necessarily exposed to radiation simply as a result of being human beings living on the Earth. Table 5 shows that there is a natural background dose of one to two hundred milli-rad per year to all tissues of the body; thus in a lifetime of seventy years a human being will accumulate a radiation dose of at least seven rads over the whole body.

natural background

Table 5

Radiation exposure

	Doses in millirad per year
Local gamma radiation in rocks	50
Cosmic radiation	25
Internal *natural* emitters	25
(C^{14} included in line above	1)
Medical radiology, other miscellaneous sources	20
Fall-out from explosions up to 1959	1

It is very difficult to be precise about the effects of doses of this order on human beings. To illustrate the problem let us try to estimate the long-term effect of low doses on man, taking, for example, the general life-shortening. Figure 7 shows that for mice a dose rate of 200 rad shortens life by ten weeks, about ten per cent of a mouse's lifetime. Since the effect appears linear, for 20 rad the life shortening would be one per cent. Now how can we extrapolate from mice to men? Do we assume that doses are equivalent? Do we assume that effective doses depend in some way on body size? We certainly cannot do experiments on statistically significant numbers of men to establish a human equivalent of Figure 7. And further, what is the effect of the dose coming over a long period rather than on a single occasion as with the mice in Figure 7? A radiological worker may accumulate several tens of rad over a lifetime of work (at 5 rad per year). But how should we compare this with a single dose of the same amount? Certainly the cumulative dose is likely to be less effective, but how much less? Again, take the induction of various cancers by radiation. In the range 100–1 000 rads, the Hiroshima and Nagasaki data suggest a linear relation for incidence of leukaemia. Does this persist to much lower dose rates? We know that children born to mothers who have had abdominal X-ray examinations, with foetal doses of a few rads, have a 50 per cent higher probability of death from leukaemia (in the first eight years of life) than children of non-X-rayed mothers.

This suggests that the linear relation may persist to lower dose rates (if we assume that the foetus is 5–10 times more sensitive to radiation than the adult). The extrapolation, though, could easily be overthrown by more data, which we hope will never be available.

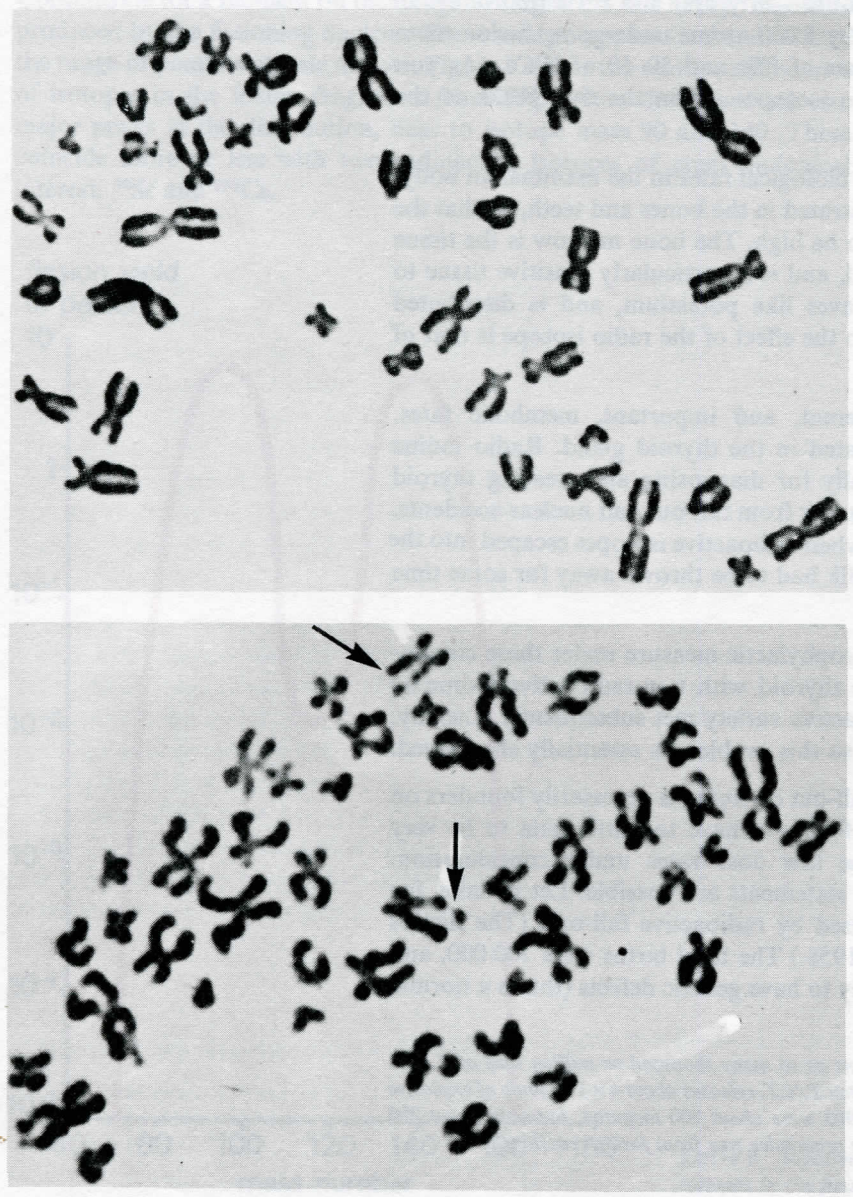
To summarize, the illnesses produced by radiation also occur for other reasons, as a result, if you like, of natural causes. For example, there is no way of telling a cancer produced by radiation from one arising from other causes. Only if we can observe a statistically significant difference between an irradiated and a non-irradiated population, can we establish, quantitatively, a radiation effect.

Genetic effects of ionizing radiation

Genetic effects produce changes in the hereditary material of the reproductive cells of an organism. These changes, which affect the reproductive cells, will have notable effects in succeeding generations, but they may not be accompanied by any visible external injury to the organism. Chromosome changes can, however, sometimes be seen at high dose rates (Fig. 8), You met this effect before, in Unit 16, where you learnt that the mutation rate could be increased markedly by exposure to ionizing radiation. Recall also the biological experiment in the Summer School.

chromosome changes

Once again it is not clear whether the effect is directly proportional to the dose and also how, in detail, it depends on the rate at which the dose is received. It is very likely that a high dose received in a short time is several times more effective in producing genetic effects than the same dose re-



(*a*)

(*b*)

Figure 8 *Photomicrographs of* (*a*) *normal chromosomes;* (*b*) *the same chromosomes broken by irradiation with an X-ray dose of* 50 r. *Arrows indicate two single breaks.*

ceived at a lower rate over a longer period. (We define high dose rates as greater than 25 rads per minute and low dose rates as less than one rad per minute.)

The Hiroshima 'atomic' bomb, which consisted of ^{235}U, probably contained about 2.5 kg undergoing fission. Up to 1963 (the point at which the Test-Ban Treaty was signed) the total radioactivity released into the environment by nuclear tests was about 10^{14} curie.* The subsequent French and Chinese tests have increased this, but probably not significantly.

Fall-out and its effects

In the long term, what goes up, comes down. So the radioactive products released into the atmosphere by a nuclear explosion are eventually distributed over the surface of the Earth. The amount of this radioactive material is decreasing continually as the fission products decay into more stable forms, with different half-lives for the different isotopes.

This radioactive decay can be approximately represented by a law of the form $R_t = R_0 t^{-1.2}$ where R_t is the radioactivity at time t and R_0 the value at some reference time. But some of the fission products have much longer half-lives than others, and as time goes on they will become more and more predominant in a given batch of fall-out as the faster-decaying isotopes reach stable end forms. ^{90}Sr (half-life~28 years) and ^{137}Cs (half-life~31 years) are cases in point. For every 1 000 atoms undergoing fission there are eventually formed 30–40 atoms of ^{90}Sr and 50–60 of ^{137}Cs. (As you can see from Figure 9, these two isotopes are in the two peaks of the product-distribution curve.)

These two isotopes have different biological fates in the mammalian body. Strontium, like calcium, is concentrated in the bones and teeth, so that the dose rate to the bone marrow can be high. The bone marrow is the tissue in which blood cells are produced, and is a particularly sensitive tissue to radiation damage. Caesium behaves like potassium, and is distributed evenly through the body fluids, so the effect of the radio isotope is that of whole-body radiation.

Other radio isotopes have different, and important, metabolic fates. Iodine, for example, is concentrated in the thyroid gland. Radio iodine (^{131}I), which can be used clinically for diagnosing and treating thyroid conditions, is also a short-term danger from fall-out and nuclear accidents. After the Windscale** accident, when radioactive isotopes escaped into the environment, locally produced milk had to be thrown away for some time because of unsafe levels of ^{131}I.

Iodine tablets can be used as a prophylactic measure under these circumstances, in order to saturate the thyroid with non-radioactive iodine so that it will not take up the radioactive variety met subsequently. Luckily, ^{131}I has a short half-life (8 days) so this problem is essentially short-lived.

Any discussion of the effects of fall-out on humans necessarily founders on the point which we have met before—we have too little data to be very definite about the effects at the low dose rates under consideration. Occasionally some more specific statements are possible. Let us take, for example, the genetic defects caused by radioactive fall-out. (The figures refer to England and Wales for 1958.) The total births were 700 000, and about 4 per cent of these are likely to have genetic defects (this is a normal

** It is usual to talk of nuclear explosions as so many thousand or million tons of T.N.T. equivalent (kilotons or megatons). 1 kiloton T.N.T. releases about 4×10^{12} joule of explosive energy. The total nuclear tests up to 1963 were about 500 megaton, but only about 200 megaton was from fission processes, the remainder was from fusion reactions.*

*** In Cumberland, UK.*

figure, taken from a United Nations Report.) Possibly 90 per cent of these genetic defects are due to chemical causes, or mechanical accidents, and 10 per cent are due to background radiation (a Medical Research Council report, published in 1956, says this figure is between 2 and 20 per cent). So we would expect 2 800 defects due to natural radiation.

A very few mutations are undoubtedly beneficial, but the consequence of a beneficial mutation becomes apparent only in the slow process of biological evolution (see Unit 19). A mutation which does great harm will probably be eliminated from the population since people bearing this gene may not survive to the age of reproduction. But a slightly deleterious mutant gene could persist much longer and could do harm, though not such serious harm, to a much larger number of individuals. We will try to make an estimate of the genetic effects of nuclear testing, for example, after we have discussed the problem of nuclear weapons.

Nuclear fission and fission products

The process of nuclear fission produces from a heavy nucleus two daughter nuclei plus a number of fast neutrons (Unit 31). It also produces a large amount of energy which is made available, as you have already learned, by a disappearance of some of the mass of the fissioning nucleus.

Concentrate for a moment on the daughter fragments, the heavy fragments produced by the fissioning nucleus. These tend to appear in the middle of the range of possible atomic masses. Figure 9 shows the relative abundance of isotopes in the fission fragments from ^{235}U. Note that there are two major peaks in the distribution, near to isotope mass 90 and 140. These coincide more or less with two radioactive isotopes of great biological interest, ^{90}Sr and ^{137}Cs.

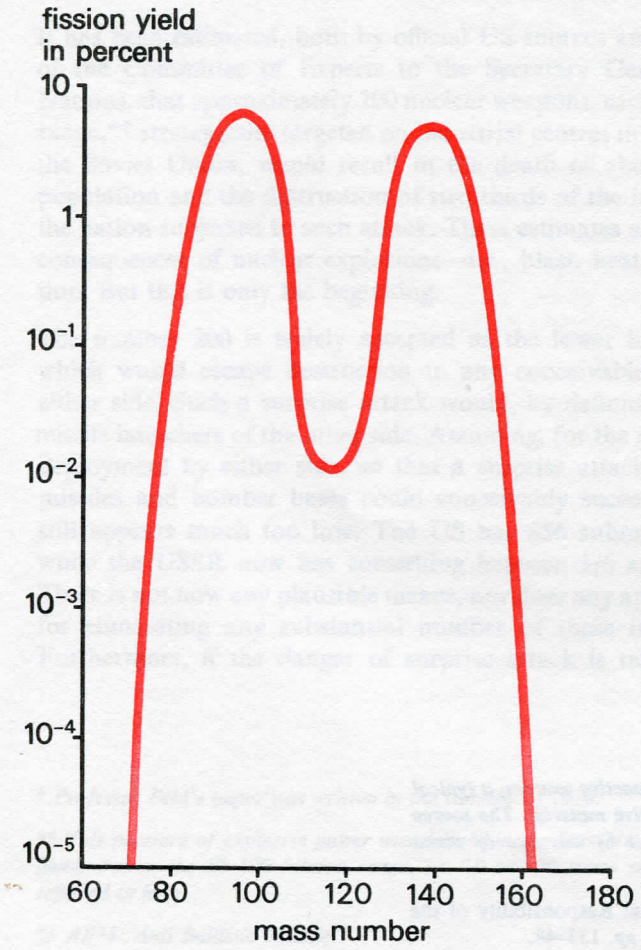


Figure 9 Relative abundance of isotopes in the fission fragments of ^{235}U.

One kilogram of ^{235}U, in fissioning will produce just under one kilogram of fission products, with a total radioactivity of order of magnitude 10^{11} curies. This is a very great deal of radioactivity.*

(In England and Wales the background radiation dose to human beings is 50 per cent due to rocks, 25 per cent due to cosmic rays, and 25 per cent to naturally occurring radioactive isotopes incorporated internally in the body, such as ^{14}C or ^{40}K.)

The extra radiation due to human activities can be divided into two parts. The first part comes from medical and industrial radiology; this is about 20 per cent of the natural background and so will cause 560 extra defects. The second part is due to fall-out which, since the cessation of testing, has settled down at about 1 per cent of natural background. This, then, causes 28 extra defects. So you can see that genetic defects due to fall-out, although quantifiable, remain small compared with those due to natural background. But the calculation takes no account of the effects of radiation of the foetal stage and the associated increase in the rate of spontaneous abortion. It should be borne in mind, however, that calculations of this kind are very crude, and some authorities would take a much more cautious line.**

The fall-out problem caused sufficient concern for a UN initiative for an atmospheric Test-Ban Treaty. This treaty was signed in 1963.

This appendix has necessarily been brief. If you wish to read further consult Peter Alexander's *Atomic Radiation and Life*, Penguin Books, (A399). This is a well-written, fascinating and authoritative account.

* *To help you get some feeling for the order of magnitude of radioactive sources, a typical luminous wrist watch contains less than* 1 *microcurie of radioactive material. The source used by Dr. Stannard during Millikan's experiment* (*TV, Unit* 6) *was one of about* 1 *microcurie.*

** *For instance, J. W. Gofman and A. R. Tamplin in* The Social Responsibility of the Scientist, *The Free Press—Collier Macmillan, New York*, 1971, *pp.* 133–48.

Appendix 3 (White)

B. T. Feld

On the Consequences of Nuclear War—A Reminder

The Strategic Arms Limitation Talks (SALT)—soon to be resumed* in Helsinki—appear to have made some progress towards a USSR–US agreement to limit the deployment of strategic nuclear weapons. We all share the hope for their rapid success.

However, it is vital to recognize that the agreement which is now being sought—a limitation of strategic systems at essentially current levels (with some possible readjustment in the distribution of missiles among the various systems now deployed)—is only a small, though essential, step towards the desired end of reducing and eventually eliminating the dangers of a nuclear war.

Everybody recognizes what an unmitigated catastrophe a nuclear war would be. The release of even a small portion of the fission and fusion energy now stored in nuclear weapons would take a fantastic toll of destruction and death, extending far beyond the borders of the nations under attack. It is the impossibility of avoiding such a consequence on both sides—irrespective of how or by whom nuclear war were initiated—that has deterred and continues to deter the use of nuclear weapons.

But what if deterrence should fail? We present below some facts and figures on the consequences of some possible nuclear wars. There is nothing new in these data or the computations involved. But I believe they are insufficiently publicized, not only among laymen but among scientists as well.

It has been estimated, both by official US sources and in the 1967 report of the Committee of Experts to the Secretary General of the United Nations, that approximately 200 nuclear weapons, each in the low megaton range,** strategically targeted on industrial centres in the United States or the Soviet Union, would result in the death of about one third of the population and the destruction of two thirds of the industrial capacity of the nation subjected to such attack. These estimates are for the immediate consequences of nuclear explosions—i.e., blast, heat, and prompt radiation. But this is only the beginning.

The number 200 is widely accepted as the lower limit of the weapons which would escape destruction in any conceivable surprise attack by either side. Such a surprise attack would, by definition, be aimed at the missile launchers of the other side. Assuming, for the moment, no ABM*** deployment by either side, so that a surprise attack against land-based missiles and bomber bases could conceivably succeed, the number 200 still appears much too low. The US has 656 submarine-based missiles, while the USSR now has something between 1/6 and 1/3 this number. There is not now any plausible means, nor does any appear on the horizon, for eliminating any substantial number of these in a surprise attack. Furthermore, if the danger of surprise attack is taken at all seriously,

* *Professor Feld's paper was written in the summer of* 1970.

** *This measure of explosive power was defined in the footnote on p.* 94. *The Hiroshima bomb was in the* 50–100 *kiloton range, i.e.* 10 *to* 100 *times smaller than the weapons referred to here.*

*** *ABM: Anti Ballistic Missile.*

both sides are likely to adopt a 'launch on warning' strategy, such as is already in effect for long-range bombers; but this would only insure that all, rather than around half, of all nuclear weapons were used in such a war. Furthermore, we have not counted the tens of thousands of 'tactical' nuclear weapons available to the armed forces on both sides.

The consequence of all this is that, in a nuclear exchange between the superpowers, whatever its cause, both sides may expect closer to a thousand multi-megaton weapons delivered on a variety of targets including all the major and minor cities. It is doubtful if America and Russia could survive such attacks.

But we have not even begun to consider the consequences of radioactive fallout and atmospheric contamination. Over a wide range of meteorological conditions, such as generally apply in the temperate zones, an explosion involving around 1 megaton of fission yield, at an altitude such that the fireball touches the ground, will result in a lethal level of fallout (greater than 500 rads) over an area of approximately 1 000 square miles (2 500 km^2). Thus, one thousand 5-megaton bombs (or 5 000, 1 megaton bombs) aimed in a first strike at 1 000 land-based missiles (which is approximately the number now emplaced in the USA and USSR) could cover with lethal fallout an area of 5 000 000 square miles, which is approximately the area of the USA. Furthermore, the radiation intensity of the fallout decreases only very slowly with time—by a factor of 10 for each 7-fold increase in the time interval. From such fallout there is no hiding and no running away; nor does fallout respect national boundaries.

The existence of an anti-ballistic missile system would only make things worse. The strategy of the attacker would then be first to eliminate the ABM or, failing that, to exhaust its defensive missiles through saturation, and then to proceed as he would have in the absence of the ABM. So the effects would merely be compounded.

Furthermore, in this case, even if most of the nuclear explosions were high in the atmosphere, the amount of atmospheric contamination would be exceedingly large. The fission products in the atmosphere, and also the neutron-induced radioactive ^{14}C, would be spread uniformly, first in the northern hemisphere, and eventually throughout the globe, and the longer lived fission products (e.g. ^{137}Cs, ^{90}Sr) would eventually find their way to the surface of the earth, contaminating everything.

What are the long-range effects of such radiation? Considerable controversy still surrounds the question of the long-range effects of the ^{90}Sr deposited as a result of all atmospheric weapons tests preceding the test-ban (approximately 200 megatons of fission yield); whether or not this has led to an observable increase in the 'normal' incidence of leukaemia in children, no one can argue that a sufficiently large deposition of ^{90}Sr would produce precisely this result. Furthermore, whatever one's position in regard to the controversies concerning the magnitude and significance of the genetic damage and other harmful effects of ^{14}C and the long-lived fission products, we are dealing, in the case of a nuclear attack, with fission yields far exceeding 200 megatons, much of it exploded at low altitude, which would insure the deposition of the fission products and neutron-induced radionuclides in a relatively short time. As a minimum, a nuclear first strike without ABM would involve some 5 000 megatons and an ABM, whether successful or unsuccessful, could well increase this by a factor between 4 and 10 (assuming a few large, long-range and approximately 10 smaller, short-range defending missiles per attacking

Appendix 3

one). So we must assume that a full-scale nuclear war would lead to something in the range of 20–50 000 megatons of fission energy release.

The previously mentioned test-released fission products from approximately 200 megatons is estimated (Report of the UN Scientific Committee on the Effects of Atomic Radiation, 1964) to have given rise to an average total dosage of around 100–200 millirems (rem-röntgen equivalent in man) to all individuals in the Western hemisphere and about an equal amount of ^{90}Sr irradiation in human bones. Multiplication by the factor 100–250 due to a full-scale nuclear war, would mean 10–50 rem per person. Perhaps this would not be sufficient to extinguish mammalian life on the planet, but certainly world-wide consequences would be very serious. Another factor of 10, which is well within the realm of possibility if present trends in nuclear arms continue, would represent the ultimate insult (used in its medical sense) to mankind, and could well spell its end.

Appendix 4

Glossary

IONIZATION CHAMBER A device for measuring the amount of ionizing radiation. Consists of a gas-filled chamber containing two electrodes (one of which may be the chamber wall) between which a potential difference is maintained. The radiation ionizes gas in the chamber and an instrument connected to one electrode measures the ionization current produced.

DEEP THERAPY The treatment of cancerous tissue below skin depth by irradiation with ionizing radiation. The radiation must be capable of penetrating tissue to depths of the order of 10 cm or more and its effect should, ideally, be as localized as possible.

NEUTRON THERAPY The use of neutron beams for deep therapy. In this case the ionizing radiation is not the primary neutron beam but the 'knock-on' protons produced by collisions between neutrons and atomic nuclei in the tissue (particularly the hydrogen nuclei).

PURPURA Condition characterized by the occurrence of purple coloured spots or patches. These are due to bleeding beneath the surface of the skin.

PETECHIAE Small red or purple spots on the skin resembling fleabites (from the Italian for fleabite), caused by haemorrhage between the skin layers.

EPILATION Fall out or removal of hair by roots.

Self-Assessment Questions

Sections 34.1 and 34.2.1

Question 1 (*Objectives I.7 and IV.3*)

Suppose you had to write an essay assessing the major social, economic and political consequences of large-scale artificial nitrogen fixation processes.

1 Which of the statements listed in the list below (A–D, 1–5) would you note down as being *relevant* ones for inclusion in your essay? (Note: Not all the statements are true.)

2 Which of the statements you have chosen would be of importance if you were referring to the socially beneficial consequences?

3 Which of the statements you have chosen would you regard as relevant to the first of the three categories (of social effects of science and technology) discussed in 34.1 (pp. 58–60)?

4 In considering the development of the nitrogen fixation process, which of the statements in the list would you say are related primarily to
(a) the intrinsic scientific logic of nitrogen fixation;
(b) the demands and possibilities of technology;
(c) the extrinsic demands and pressures of society?

A.1 The reaction between hydrogen and nitrogen to form ammonia is an exothermic reaction.

A.2 Nitrogenous compounds are present in exhaust emissions from motor cars.

A.3 Fixed nitrogen is needed for the manufacture of explosives.

A.4 Consumption of fertilizer nitrogen in India increased fourfold between 1955 and 1964.

A.5 The Haber-Bosch process provided Germany and the Central Powers with the nitrates they needed to continue the First World War.

B.1 Consumption of fertilizer nitrogen in the USA and Canada decreased by some 300 000 tons between 1955 and 1956.

B.2 The main sources of saltpetre are to be found in a few places outside Europe.

B.3 Some bacteria convert ammonium compounds into nitrates.

B.4 Nitrogenous fertilizers can be manufactured from coal.

B.5 For growth, plants require chemically combined nitrogen only in the form of dissolved nitrates.

C.1 Some bacteria decompose nitrogenous compounds and release nitrogen to the atmosphere.

C.2 Water supplies in some parts of the world have become contaminated by excessive quantities of nitrogenous compounds.

C.3 Nitrogenous fertilizers are not the only cause of eutrophication.

C.4 Fritz Haber was driven from his University post because he was Jewish.

C.5 Land plants cannot extract nitrogen directly from the atmosphere.

D.1 For growth, animals require chemically combined nitrogen only in the form of dissolved nitrates.

D.2 The use of nitrogenous fertilizers is much greater in the developed than in the underdeveloped countries, and the difference is increasing.

D.3 Nitrogen-containing compounds are essential components of all living organisms.

D.4 Nitrogenous fertilizers can double or even treble the yield of grain crops.

D.5 The potential benefits of science do not automatically apply where they are most needed.

Section 34.2.2

Question 2 (*Objectives I.8 and IV.3*)

You are asked to sum up the pros and cons of the large-scale development of electrical power generation from nuclear energy, involving a hundred-fold increase over the next quarter-century.

(i) Which of the statements below (A–D, 1–5) would you select as being relevant to this assessment?
(Note: Not all the statements are true.)

(ii) Of the statements you have chosen, which would in your view be important to an argument
(a) in *favour* of such a large-scale development of nuclear power?
(b) *against* such a development?
(c) though relevant, neither clearly in favour nor clearly against?

(iii) Of the statements below, and in relation to the large-scale development of nuclear power, which do you think relate mainly to
A the internal logic of the relevant science
B the demands and possibilities of technology
C the external demands and pressures of society
D none of the above (because irrelevant or factually incorrect)?

A.1 Gross national product per capita in the USA is more than twenty times higher than in Africa.

A.2 Ordinary uranium (^{238}U) cannot be used in a nuclear reactor. Production of the fissile uranium isotope (^{235}U) is extremely expensive. Nuclear power is therefore likely to be within the means of only the most developed countries.

A.3 Nuclear power plants produce vast quantities of radioactive materials.

A.4 Nuclear power reactors are so dangerous that it is difficult to persuade insurance companies to insure them.

A.5 Coal, oil and natural gas should be regarded as raw materials for the chemical industry and not as sources of energy.

B.1 The indications are that there is no threshold for the long-term effects of ionizing radiation. Consequently, *any* release of radioactivity to the environment is harmful, and so there should not be any further expansion of the nuclear power programme.

B.2 A nuclear reactor can be used to 'breed' fissile plutonium from ordinary, non-fissile uranium.

B.3 Coal-fired power stations actually pollute the environment far more than nuclear power stations do.

B.4 There is a close correlation between per capita energy consumption and per capita gross national product.

B.5 Cheap electrical energy would open up vast perspectives for industry and agriculture.

C.1 The world's population is likely to double over the next twenty-five to thirty years.

C.2 The probability of a serious accident with a nuclear reactor is less than one in a hundred thousand.

C.3 There is no evidence of any correlation between energy consumption and standard of living.

C.4 Estimated costs of electricity from nuclear energy are likely to prove optimistic when the costs of improved plant safety and better waste disposal systems are taken into account.

C.5 The safe disposal of the large quantities of radioactive waste materials that would be produced, on current forecasts of nuclear energy development, would pose very serious problems.

D.1 If the generation of electrical energy does not keep pace with the growth in the world's population, society will be faced with even greater dangers than those that might arise from the nuclear power programme.

D.2 The expansion of nuclear power on the scale envisaged would mean a great proliferation of nuclear reactors and hence of capacity to make nuclear weapons.

D.3 The cost of electricity from nuclear power stations is likely to fall considerably below that of electricity from coal- or oil-fired stations.

D.4 The world's known reserves of fossil fuels will be insufficient to meet forecast energy requirements by the end of this century.

D.5 Nuclear power plants are likely to discharge dangerous amounts of radioactive waste materials into the biosphere.

Question 3 (*Objective I.8*)

The United Nations *Statistical Yearbook* (1969) gives the following figures for total energy consumption per capita (in kilogrammes of 'coal equivalent') for the year 1965:
Latin America: 579, Western Europe: 3 050,
Canada and USA: 9 053, Africa: 283,
Asia (excluding China but including Japan): 324.

The same source gives the per capita GNP in 1965 for Asia (excluding China but including Japan) as 190 US dollars.

Using these figures, and those in section 34.2.2, decide which of the following statements are (A) warranted or (B) unwarranted.

1 There is no correlation between per capita GNP and per capita energy consumption.

2 There is a partial correlation between these two quantities.

3 There is a complete correlation between them.

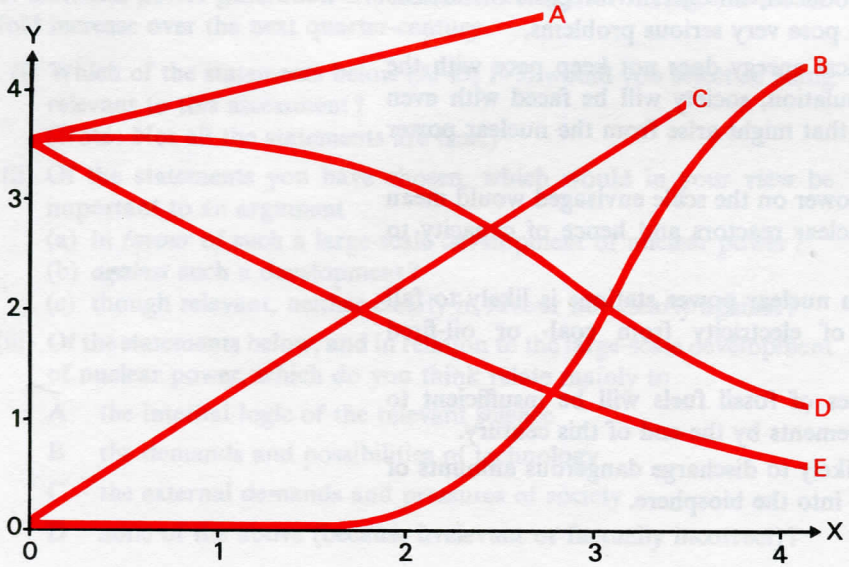
4 Per capita GNP is directly proportional to per capita energy consumption.

5 If the GNP of Canada and the USA (in 1965) had been some 35 per cent higher the figures would show an approximately proportional relation between GNP and energy consumption. (Hint: Drawing a graph would help you decide on (4) and (5).)

Appendix 2

Question 4 (*Objective I.9*)

Which of the graphs shown in Figure 10 exhibits a threshold effect?



Question 5 (*Objective I.11*)

Which of the following biological effects of radiation are (A) acute, (B) long-term, (C) genetic.

1 Leukaemia
2 Mutation
3 Vomiting and diarrhoea
4 Loss of appetite
5 General life-shortening
6 Cancer
7 Emaciation
8 Chromosome rupture
9 Sterility
10 Epilation

Question 6 (*Objective II.6*)

'It is difficult to be certain about the effects of small doses of ionizing radiation on man':

Which of the following statements support the above conclusion?

A.1 If the dose is below the threshold level for man no effects will be observed.

A.2 Small doses of ionizing radiation are too weak to penetrate the skin and so their effect is too small to be observable.

A.3 Even in experiments on the effects of small doses of radiation on laboratory animals, it is difficult to obtain statistically significant results.

B.1 The effects of radiation on man are known to be quite different to the effects on laboratory animals, so it is not possible to predict the former from observations of the latter.

B.2 One cannot do systematic experiments on the effects of ionizing radiation on man.

B.3 Whereas it is possible to be certain about physical effects, biological effects are always subject to uncertainties.

C.1 It is difficult to distinguish between the effects of such small doses and the effects of the natural background radiation.

C.2 The results of experiments on laboratory animals are difficult to apply to man.

C.3 It is difficult to measure such small doses of radiation with sufficient accuracy.

Question 7 (*Objective II.7*)

The fission products ^{90}Sr and ^{137}Cs constitute a greater biological hazard than others because:

(Select the statements which you think are both true and relevant to an explanation.)

1 They are among the most abundant of the radio-isotopes produced in nuclear fission.

2 They emit particularly penetrating radiation.

3 Their half-lives are fairly long.

4 They are concentrated in particular parts of the body.

5 Strontium and caesium compounds are toxic.

6 They are distributed evenly through the body fluids, so they have a 'whole-body' effect.

7 They are concentrated in the thyroid gland.

8 Their specific activity (curies per gramme) is higher than that of most other fission products.

Self-Assessment Answers and Comments

Question 1

1 We think the relevant statements are:

A3 A5 B2 B5 C2 C5 D2 D3 D4 D5

You may have considered including A4. If the wording had been 'consumption of fertilizer nitrogen in India increased by *only* a factor of four between 1955 and 1964', there would, perhaps, have been stronger grounds for its inclusion. What is really relevant to the assessment is not the increase that took place in India, which in absolute amount and in relation to needs was quite trifling, but the enormous and widening gap between India and the USA.

Likewise, B1 is really beside the point, or of quite marginal relevance in assessing the *major* social, economic and political consequences.

A1 and A2 are true but irrelevant, as are B3, B4, C1, C3 and C4. (In assessing the *consequences* of large-scale artificial nitrogen fixation the fact that nitrogen compounds can *also* be got from coal as well as from atmospheric nitrogen is not, we think, of much relevance.)

D1 is false (because animals require chemically combined nitrogen in the form of amino acids).

2 In our view, the important statements in referring to the socially beneficial consequences are:

B5 C5 D3 D4

To these we would possibly add, as marginal cases:

A3 A4 D2 and D5.

We rate A3 as marginal because though explosives have undoubtedly been socially beneficial in their use in mining and construction, their military use has perhaps been less clearly beneficial in the main.

A4 has, of course, been of limited social benefit to India, but we think it is a drop in the ocean.

D2 is a valid point if you are emphasizing the actual social benefits to the developed countries and (by way of contrast) the *potential* benefit to the underdeveloped ones. Taken *globally* this statement seems to us to indicate a *failure* to apply this technology in anything like an optimal way to the benefit of society. D5 is really a comment on this last point.

3 We suggest C2 is the only clear example (from the list) of *unforeseen* and undesirable side-effects of a desirable development.

4 (a) Our choice of statements related primarily to the intrinsic scientific logic of nitrogen fixation is:

A1 B3 B5 C5 D3

You may have included C1 as denitrifying bacteria contribute in the *negative* sense to nitrogen fixation.

4 (b) Here, our choice is:

A3 B4 D4

In the sense that the intrinsic scientific fact of B3 is applied in agriculture, you might include B3 in this category as well as in (a).

4 (c) We suggest:

A3 A5 B2 D2 D5

A4 and B1 could also be added, but, for reasons we have given above, we would regard these as marginal to the main issue.

Question 2

(i) We think

A3 A5 B1 B3 B4 B5 C1 C2 C4 C5 D1 D3 and D4

are definitely relevant. You might add B2 because this (true) statement has the implication that nuclear power stations using such 'breeder reactors' can produce more fissile material than they use up—so there will be an effectively unlimited supply of the required fissile material. You might (marginally) add A1 because the gap between the developed countries (e.g. the USA) and the underdeveloped ones (e.g. most of Africa) in terms of GNP corresponds with the gap in terms of energy consumption, and one of the reasons why there will have to be a large expansion of electrical power generation is that something must be done to start closing this gap. And (more dubiously) you might add A4 on the grounds that this reflects an objective problem in the large-scale expansion of nuclear power installations.

The statement, though essentially true, is nevertheless formulated in an exaggerated way, and this might have prompted you—we would think rightly—to have left it out of your list.

(ii) We think the best selection would be

(a) A5 B3 C2 D1 D3 D4 (B5)

(b) A3 B1 C4 C5

(c) B4 B5 C1

Comments

You might have left C2 out of the arguments in favour of nuclear power, on the grounds that 100 000 to 1 may be a very good safety factor, but it isn't good enough. There is possibly room for argument about D4, along the lines that the *known* reserves of fossil fuels may be considerably less than the actual, but as yet unknown, reserves.

We have put B5 in brackets because this point is one in favour of producing cheap electrical power, and this need not *necessarily* mean more *nuclear* power. Nevertheless, you might think B5 should go into the list, having regard to D3.

If you share Alvin Weinberg's optimism about our ability to devise effective means of disposing of our 'nuclear garbage' you might prefer to put C5 in (c) rather than (b).

(iii) Our selections are:

	1	2	3	4	5
A	D	D	A	C (D)	B C
B	A C	A B	B C	C	B C
C	C	B C	D	B	B C
D	C	D	B C	C (B)	D (C)

Comments

A2 rates D because it is factually incorrect. A4 rates (D) because the term 'dangerous' is an exaggerated one which makes the statement verge on being factually incorrect.

C3 is factually incorrect. See *SAQ* 3.

D2 is incorrect because it implies that the possession of a nuclear reactor necessarily constitutes a 'capacity to make nuclear weapons'. It is technically very easy to prevent this by proper safeguards and inspection (for instance by the International Atomic Energy Agency). The risk of proliferation of nuclear weapons has a great deal more to do with systems of separation of ^{235}U from ^{238}U, and of extraction of nearly pure ^{239}Pu from reactor fuel elements. Whether you rate D5 as C or D depends on how optimistic you are. If the statement read 'some' instead of 'dangerous amounts' and 'might' instead of 'are likely to', we would be inclined to give it an unequivocal C.

Question 3

1B 2B 3A.

If you arrange the five regions in rank order of GNP per capita and of energy consumption per capita, the order is exactly the same in both cases.

That is what is meant by complete correlation.

4B 5A

A graph of GNP against energy consumption (per capita) would be very nearly a straight line if the (USA + Canada) GNP were about 4 650 dollars instead of 3 476 dollars.

It is instructive to compare the data in this *SAQ* with that in section 34.2.1 on production and consumption of fertilizer nitrogen.

Question 4

Graphs B and D exhibit threshold effects. The other three graphs do not. In both B and D the threshold lies somewhere between $X=1$ and $X=2$.

Notice that a plot of $(3.5-Y)$ against X would transform D into a graph rather similar in shape to B.

You might guess that D and E look as if they might have thresholds at some very large value of X (i.e. zero values unless X is *less* than some large amount). But this would only be guessing.

Question 5

1B 2C 3A 4A 5B 6B 7A
8C 9B 10A

(Of these, only 9. Sterility is not explicitly mentioned in the text. You might have guessed it from general knowledge.)

Question 6

B2, C1, C2, (A3).

Note that A1, A2, B3, C3 and B1 are factually incorrect.

Question 7

Of the statements listed, only 1 and 3 are both true and relevant.

Statement 4 is true of strontium (and relevant) but not true of caesium.

Statement 6 is true of caesium but not of strontium; even in the case of caesium it is not relevant.

Statements 2, 5, 7 and 8 are false.

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TEXT

CENTRE EUROPÉEN POUR RECHERCHES NUCLÉAIRES for Victor F. Weisskopf, *CERN Annual Report*, 1963; LONGMANS, GREEN & CO. LTD. for L. F. Haber, *The Nitrogen Problem*; PERGAMON PRESS LTD. for Alvin Weinberg, *Reflections on Big Science*; PUGWASH CONFERENCES ON SCIENCE AND WORLD AFFAIRS for Professor Feld's paper given at the twentieth Pugwash Conference; UNITED NATIONS for total energy consumption per capita and GNP per capita statistics from *UN Statistical Yearbook*, 1969.

ILLUSTRATIONS AND TABLES

MEDICAL RESEARCH COUNCIL for Table 3 in *Medical Research Council Report 1960*; ROYAL SOCIETY for Fig. 3 in *Proceedings of the Royal Society*, vol. 154, 1961; 'SCIENCE JOURNAL' for Fig. 4 in Frank Barnaby, 'Is Nuclear Power Worth the Risks?', *Science Journal*, 6 August 1970; STOCKHOLM INTERNATIONAL PEACE RESEARCH INSTITUTE for Table 1.

Notes

S.100—SCIENCE FOUNDATION COURSE UNITS

1 Science: Its Origins, Scales and Limitations
2 Observation and Measurement

3 Mass, Length and Time
4 Forces, Fields and Energy

5 The States of Matter

6 Atoms, Elements and Isotopes: Atomic Structure
7 The Electronic Structure of Atoms

8 The Periodic Table and Chemical Bonding
9 Ions in Solution

10 Covalent Compounds

11, 12 Chemical Reactions

13 Giant Molecules

14 The Chemistry and Structure of the Cell

15, 16 Cell Dynamics and the Control of Cellular Activity

17 The Genetic Code: Growth and Replication
18 Cells and Organisms

19 Evolution by Natural Selection
20 Species and Populations

21 Unity and Diversity

22 The Earth: Its Shape, Internal Structure and Composition

23 The Earth's Magnetic Field

24 Major Features of the Earth's Surface
25 Continental Movement, Sea-floor Spreading and Plate Tectonics

26, 27 Earth History

28 The Wave Nature of Light

29 Quantum Theory
30 Quantum Physics and the Atom

31 The Nucleus of the Atom
32 Elementary Particles

33, 34 Science and Society